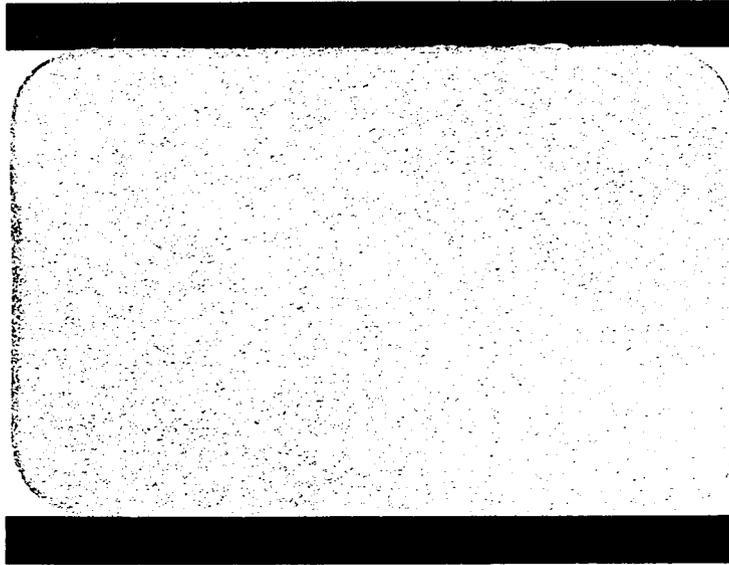


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(NASA-CR-185939) CARBON DIOXIDE FROST
CONDUCTIVITY (General Dynamics) 56 p

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CARBON DIOXIDE FROST CONDUCTIVITY

By John P. Clay

Report No. SD C-DBR05-003

Preliminary Draft

Prepared under Contract No. NAS 1-5517 by
GENERAL DYNAMICS CORP.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

July 1965

CARBON DIOXIDE FROST CONDUCTIVITY

By John P. Clay
General Dynamics/Convair

SUMMARY

Experiments were conducted to measure the thermal properties of CO_2 frost and determine the parameters effecting these properties as indicated below.

1. Determine the minimum density frost which will keep gaseous nitrogen (N_2) from being cryopumped through the CO_2 when using liquid hydrogen (LH_2) as a heat sink.
2. Determine the density of the CO_2 frost as a function of CO_2 flow rate.
3. Determine the effect of the chill-down rate of the cryogenic tank on the physical properties of the frost.
4. Measure the thermal conductivity of the frost as a function of temperature.
5. Perform task "4" above, in a gaseous CO_2 atmosphere using liquid nitrogen (LN_2) as the heat sink and in a N_2 atmosphere using LH_2 as the heat sink.

All frost growths were made in quartz tubing in one atmosphere of helium with a controlled rate of injection of CO_2 .

The experiments demonstrate that CO_2 can be frozen to an overall density of 27.6 lbs per cubic foot and thermal conductivity of .0223

BTU/(hr)(ft)²(°R) in a CO₂ atmosphere obtained with a vacuum purge. At the end of two hours in a CO₂ atmosphere, the above density and conductivity had changed to 48.5 and .0017 respectively. The rate of tank chill does not appreciably affect the overall density of a CO₂ frost growth but does affect the density distribution through the ice and the thermal conductivity. The slowest chill rate produced the lowest thermal conductivity. The lowest density CO₂ frost which will stop N₂ from being cryopumped internally is approximately 100 lbs per cubic foot in density.

INTRODUCTION

Previous experimentation by the National Aeronautics and Space Administration, Langley Research Center (NASA LRC) indicated that carbon dioxide (CO₂) frost was a good cryogenic insulator. The NASA LRC was considering the use of CO₂ frost as an insulation component for a liquid hydrogen (LH₂) fueled hypersonic aircraft due to the combined insulative effects of sublimation, transpiration and low conductivity. To obtain the insulative properties, the CO₂ was frozen in a quartz tubing in a carefully controlled atmosphere using LH₂ or LH₂ as the heat sink. The frost was formed by first purging the quartz tubing with helium, closing the system, then injecting CO₂ gas into the system at a controlled mass flow rate per unit of freezing area. The experiments were terminated by purging the helium from the system by gases O₂ and/or N₂ then measuring the thermal conductivity, density and rate of cryopumping of the resultant frost.

SYMBOLS

A*	Area of the throat of a de Laval nozzle, square feet
g	Gravitational constant, 32.2 ft/sec ²
k	Thermal conductivity, BTU/(hr)(ft)(°R)
L	Length, feet
P	Pressure, pounds per square foot
q	Heat flux, BTU/hr
r	Radius, feet
R	Gas constant, feet°R
T	Temperature, °R
v	Specific volume, ft ³ /lb
γ	Ratio of the specific heats of a gas, C_p/C_v

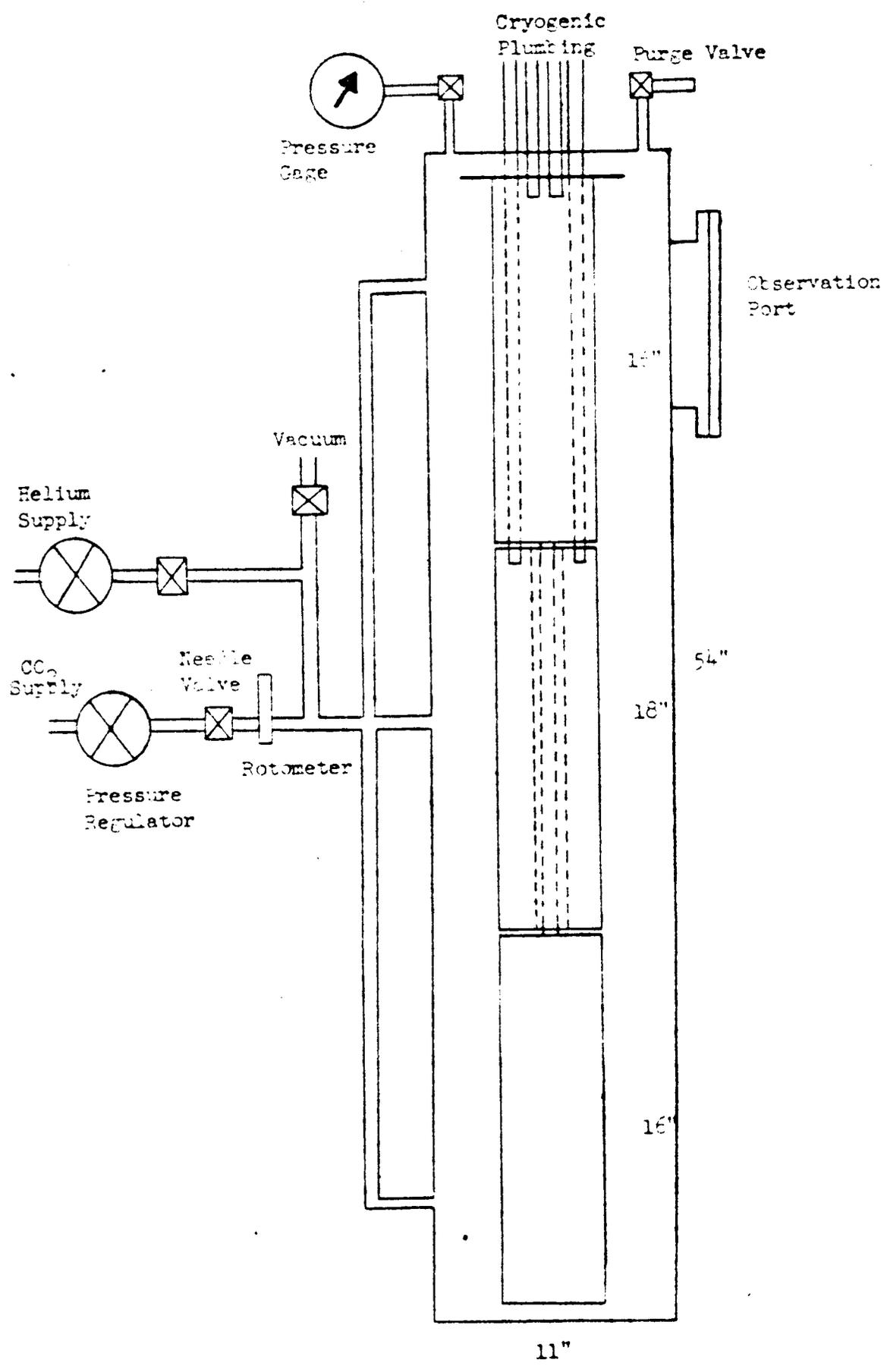
Subscripts

i	inner surface
o	outer surface
t	total

TEST APPARATUS

The guarded precision calorimeter shown in figure 1 was used to freeze the frost and obtain the required measurements. The calorimeter has a test and two guard tanks which are arranged to eliminate all heat flow into the test tank with the exception of one dimensional radial heat flux through the specimen. The

FIGURE 1. - SCHEMATIC OF PRECISION CALORIMETER USED FOR CO₂ EXPERIMENTS



cryogenic tanks are made of .125 inch copper with a outer diameter of 4.125 inches, the test tank being 18.0 inches long and the guard tanks being 16.0 inches long. The system plumbing was made of stainless steel and copper tubing and is of vacuum quality. The cryogenic lines are controlled with LH₂ quality valves which have vacuum leaks of the order of 10^{-6} standard cc of helium per sec in the open position and have a zero helium leak rate in the closed position as measured by a helium mass spectrometer with a sensitivity of 7×10^{-11} standard cc of helium per second.

The flow from the test tank for small flow rates was measured with an integrating, precision wet test meter that had a calibrated accuracy of 1% of the reading. For large flow rates, a 1000 cubic feet per hour capacity industrial gas flow meter was used. The industrial meter has an advertised accuracy of .5% of the reading, which is obtainable on a large quantity of gas. Within a single revolution, the industrial meter's output is non-linear giving an error of as much as 2% in a quantum of 1. cubic foot of measured gas. The non-linearity was sufficiently reproducible to reduce the error to 1% in a quantum of 1. cubic foot of measured gas.

On the first two experiments, the O₂ flow rate was controlled with a pressure regulator and an integrating, precision wet test gas flow meter. The O₂ flow rate was difficult to control and the meter was inaccurate due to perturbation of the water seal and was awkward to use. To correct these problems they were replaced by a pressure regulator, needle valve and rotameter. Honney (2) shows that the mass flow through a sonic

or supersonic nozzle is a function of the molecular weight of the gas, the temperature, area at the throat and the total pressure as shown in equation (1)

$$\dot{m} = \sqrt{\frac{\gamma}{\gamma+1}} \left(1 + \frac{\gamma-1}{2} \right)^{-\frac{1}{2}} \sqrt{\frac{P_0}{R T_0}} A^* \quad (1)$$

Utilizing this principle, the pressure regulator was adjusted to hold the O_2 supply pressure at a constant 20 pounds per square inch which is sufficient to provide the total pressure required for sonic flow. The gas was warmed with a water bath and the needle valve was opened to the area which obtained the proper mass flow rate as indicated on the rotometer. Using this arrangement, the mass flow rate was readily adjusted and had zero drift as indicated by the rotometer. For low O_2 flow rates, a rotometer with 1. standard cubic foot of gas per hour markings with a maximum capacity of 21 standard cubic feet per hour was used while for higher flow rates, a rotometer with coarse markings and maximum capacity of 2 cfm and 20 cfm was used. Both rotometers had a calibrated accuracy of 3% of the reading.

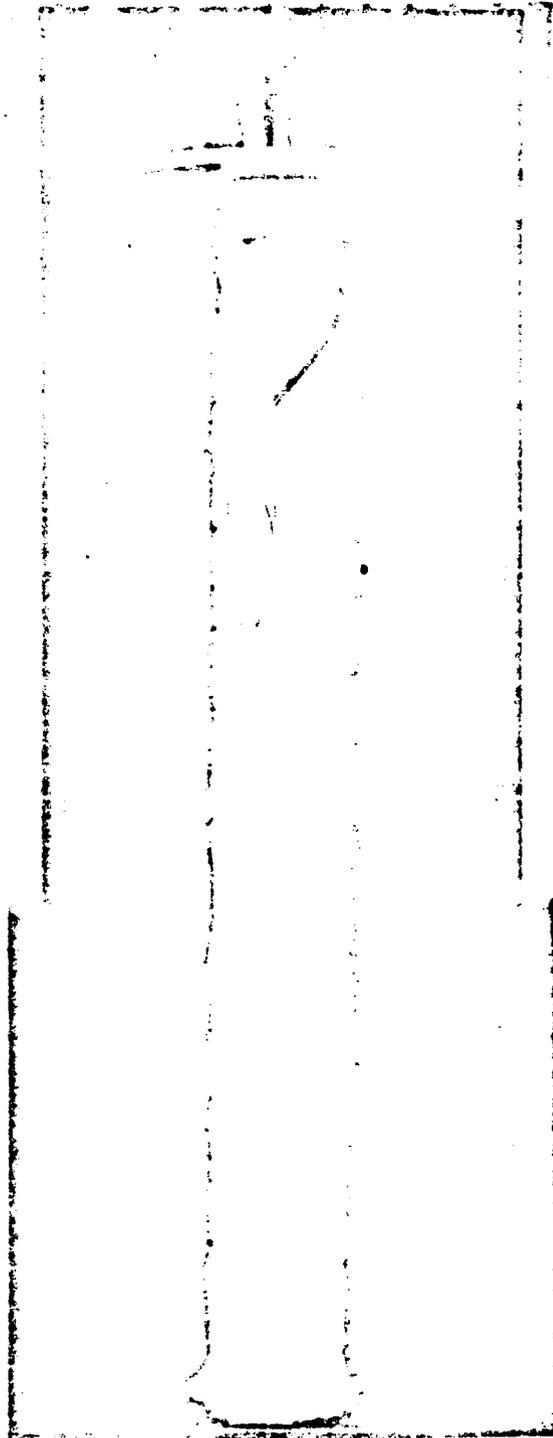
In the early experiments, the volume of the O_2 frost was measured with inside calipers and a ruler scale. As experimentation progressed, the O_2 frost was photographed against a ruled background which permitted visual measurement of the frost after the experiment was completed. To facilitate obtaining measurements, a half silvered mirror was utilized to simultaneously photograph the frost and a

ruled grid which resulted in superimposed images with a scale factor of 1.00. The weight of the CO_2 frost was measured indirectly by measuring the volume of CO_2 sublimed at the termination of the experiment with the high capacity, integrating, industrial gas flow meter.

Refrasil F-100 quartz batting was lashed to the cryogenic chambers as shown in Figure 2. The bottom of the lower guard tank was insulated with two inches of polyurethane foam and the top of the upper guard tank was insulated with cork and glass tape in an effort to freeze all of the CO_2 on the cylindrical side wall.

Thermocouples were placed 180° apart at the center of the test tank. The thermocouples were placed every .2 inches of insulation thickness with two thermocouples being used to check the uniformity of temperature distribution along the length of the cylinder. Twelve, 36 or 40 gauge, extra high purity copper-constantan thermocouples were utilized to monitor the temperatures. To minimize the number of vacuum pass throughs, the telemetry system utilizes a common constantan and ice junction with a twelve position selector switch. For this system to work properly, the cold junctions must be electrically isolated from one another. The bare junctions were coated with a thin layer of rubber cement or plastic to obtain the required electrical insulation. The thermocouples were calibrated in LN_2 and LH_2 at atmospheric pressure. The calibration experiments indicate a system accuracy of plus or minus five micro-volts.

FIGURE 3. - INSULATION USED FOR FREEZING CO₂ FROST



TEST PROCEDURES

The test procedure given below is the test procedure used on the last experiments. Deviations from this procedure are indicated in the "Experimental Data" section for each experiment along with the test results.

1. Once the apparatus was assembled, the air was vacuum purged from the quartz batting.
2. The quartz batting was backfilled with helium gas to 1.0 psig. and as required, additionally backfilled throughout the experiment to retain the 1.0 psig.
3. The guard and test cylinders were chilled with LN_2 to 350 degrees Rankine ($^{\circ}R$).
4. The guard and test cylinders were linearly chilled from 350 $^{\circ}R$ to 144 $^{\circ}R$ at a predetermined rate and continuously monitored on a strip chart recorder. The linear chilldown below 350 $^{\circ}R$ was started simultaneously with the gaseous CO_2 injection. The vacuum chamber wall was kept between 40 degrees Fahrenheit ($^{\circ}F$) and 75 $^{\circ}F$.
5. Upon completion of the chilldown, the chambers were kept filled with LN_2 . The gaseous CO_2 was injected into the quartz batting for a total of 6 (six) hours and 3.6 (zero) minutes, which time, includes the linear chilldown below 350 $^{\circ}R$. The CO_2 flow rate was closely monitored and recorded as a function of time.

6. At the end of 6 (six) hours, the gaseous CO_2 flow was terminated and the temperature distribution and heat flux through the CO_2 frost were measured.
7. With all cylinders full of LN_2 , the calorimeter was expeditiously disassembled, the frost measured for volume, then reassembled. An insulating heat shroud was added to the calorimeter in reassembling it.
8. The cylinders were refilled with LN_2 and the quartz batting was flush purged with helium.
9. Three (3), twenty (20) amp, 115 volt, heat guns were inserted into the base of the insulating shroud such that they created a rising spiral vortex about the vacuum chamber.
10. The shroud was heated until the outer CO_2 frost surface reached the sublimation point of CO_2 (350°R). The helium gas was vented from the quartz batting, as required, to retain an atmospheric pressure of $1.0 \pm .5$ psig.
11. The helium was flush purged from the system with a gaseous CO_2 purge. The CO_2 purge was continued for two hours.
12. At the beginning and end of the gaseous CO_2 purge, the temperature distribution and heat flux through the CO_2 frost was measured.
13. The calorimeter was disassembled and the volume of the CO_2 frost was measured.
14. The calorimeter was reassembled and the CO_2 frost was removed from the quartz batting by sublimation. To speed

the process of sublimation, the cryogenic was drained from the chambers and two (2) heat guns were applied to the insulation as in step #9 above.

The LN_2 tests were performed as above with the following modifications.

(a. The helium was flush purged from the quartz batting with dry N_2 for two hours. During this two hour period, the rate of cryopumping, temperature distribution and heat flux through the CO_2 frost were measured.

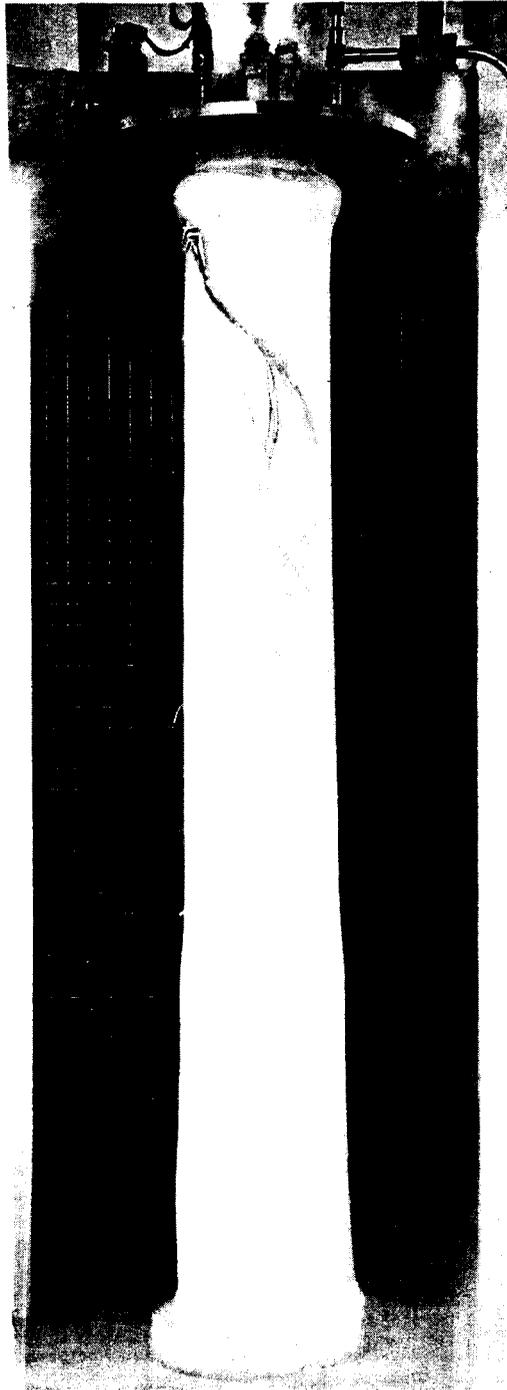
In all of the steps above, LN_2 was used in lieu of LN and the chambers were chilled to -196°F . Additional steps were included for reasons of personnel safety but they are not germane to the information desired from the experiments.

EXPERIMENTAL DATA

The results of each experiment are enumerated below. The experiments are listed with the most recent being first and the oldest last, with each experiment being given a letter designation. In all experiments involving a change in the heat sink cryogenic, between LN_2 and LN , the change in temperature created temperature stresses which made numerous cracks in the CO_2 frost growth.

The experiments indicate that the partial pressure of helium in the atmosphere of the quartz batting during frost growth greatly effect the physical properties of the frost. Figure 3, from experiment "N" shows a CO_2 frost growth which is very dense and clear. This demonstrates what occurs when the helium pressure is allowed to drop well below fifteen psia while the frost is being grown.

FIGURE 3. - CO₂ FROST GROWTH
EXPERIMENT "N"



EXPERIMENT "A"

Experiment "A" was the final liquid hydrogen test. The results are tabulated below. The CO_2 was frozen at a rate of 3.0 SCFH per square foot of cryogenic tank for a time interval of six hours and no thinner. The cryogenic tank was chilled from 300°K to 38.°K over a 80. minute time interval.

A plot of the thermal conductivity as a function of temperature is given in Figure 4. The CO_2 pressure regulator broke during the early stages of step No. 12 of the test procedure. This accident made it impossible to obtain an accurate CO_2 cryopumping rate at that time. The heat gains were unable to raise the CO_2 frost temperature to 350°K as evidenced by the change in frost thickness.

Test Procedure Step No.	C	Ca	Cb	Cc
Thermal Conductivity (BTU)/(hr)(ft)(°K)	.031	.064	.0927	.154
Warm Temperature (°R)	349.	318	300	350.
Cold Temperature (°R)	38.	38.	38.	38.
Density (lb./ft ³)	27.8	30.0	27.8	69.
Atmosphere	He	N ₂	CO ₂	CO ₂
Initial Rate of Cryopumping (SCFH/ft ²)	-	7.	unk.	-
Final Rate of Cryopumping (SCFH/ft ²)	-	2.	-	100.
Chamber Wall Temperature (°F)	50.	58.	100.	213.
CO ₂ Frost Thickness (Inches)	.70	.72	.72	.78"

SEARCH DEPTH EFFICIENCY AS A FUNCTION OF TEMPERATURE

EXPERIMENT "A"

100% Atom Spacing

10% Nitrogen Atoms/cm

10% Atom Spacing

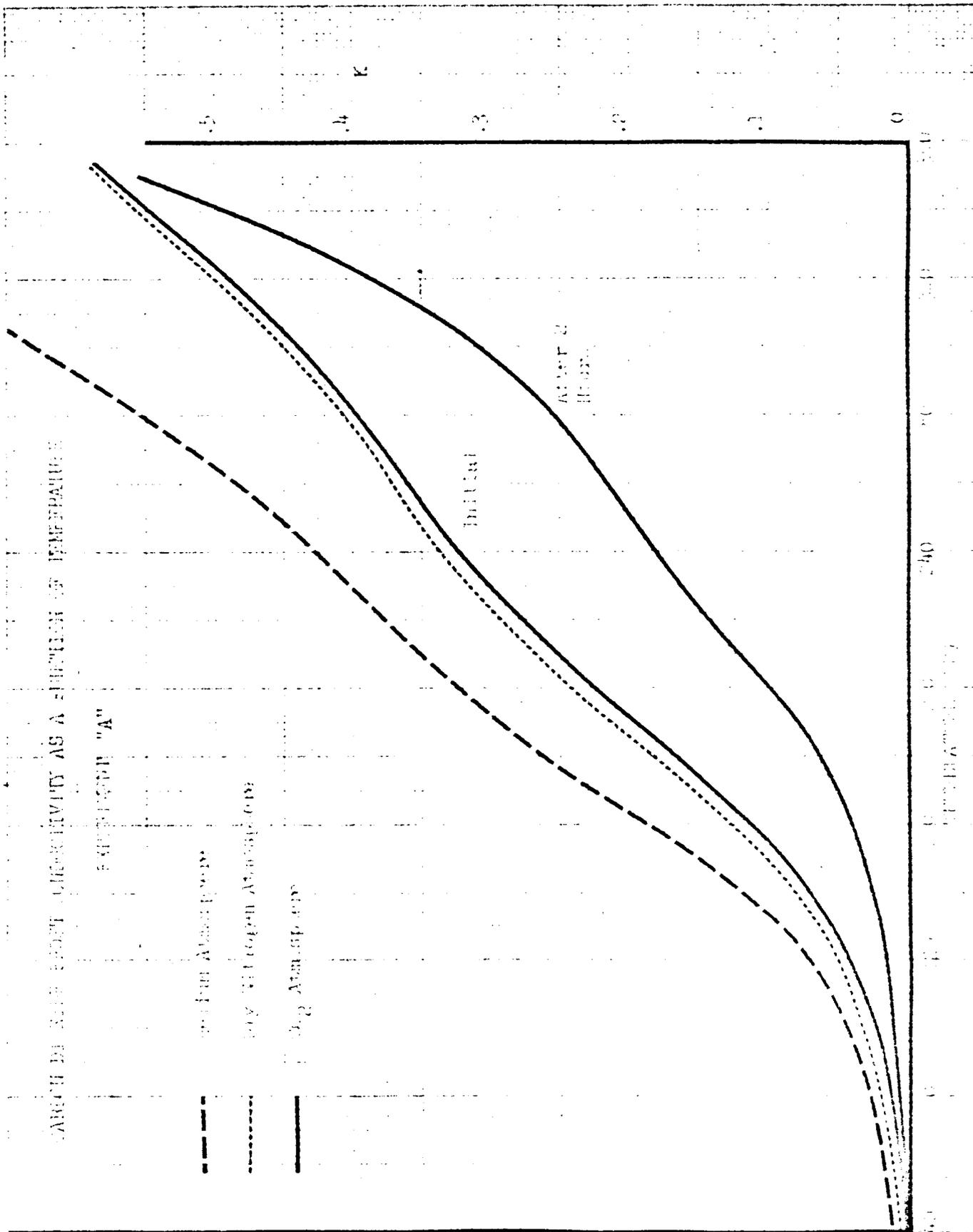


Figure 4

EXPERIMENT "B"

The CO₂ frost was frozen at a rate of 3.0 SCFH per square foot of cryogenic tank for a time interval of six hours and no minutes. The cryogenic tank was chilled from 350°R to 13°R over a one hour time interval. A plot of the thermal conductivity as a function of temperature is given in Figure 5 and additional data is listed below.

Test Parameters - Step B.

	6	12	17
Thermal Conductivity (BTU)/(hr)(ft)(°R)	.098	.100	.125
Warm Temperature (°R)	263.	350.	350.
Cold Temperature (°R)	139.	139.	139.
Density (lb./ft. ³)	30.6	30.6	73.5
Atmosphere	He	CO ₂	CO ₂
Initial rate of cryopumping (SCFH/ft. ²)	-	6.93	-
Final rate of cryopumping (SCFH/ft. ²)	-	-	9.24
Chamber Wall Temperature (°F)	51.5	121.	196.
CO ₂ Frost Thickness (inches)	.655	.655	.75

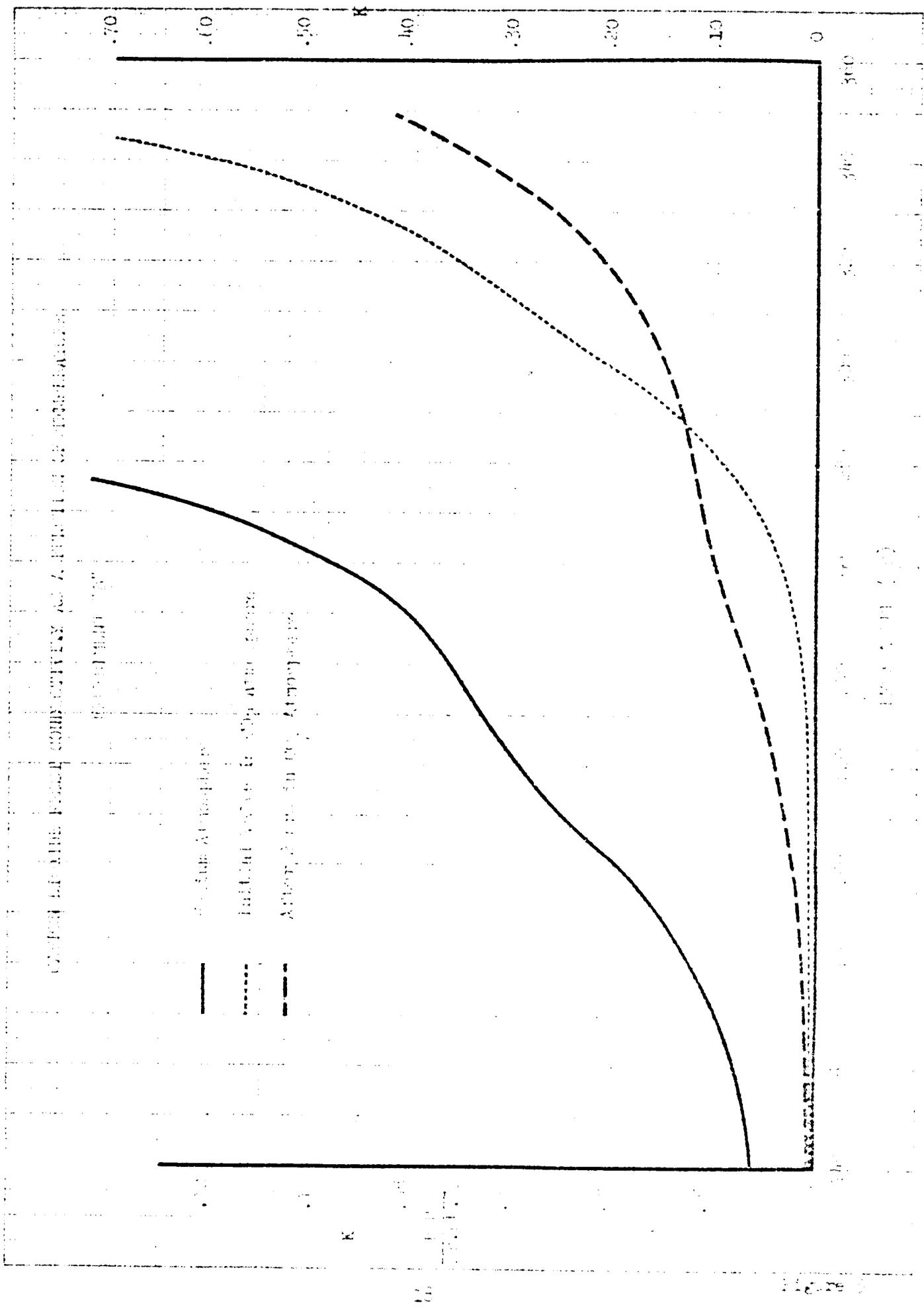


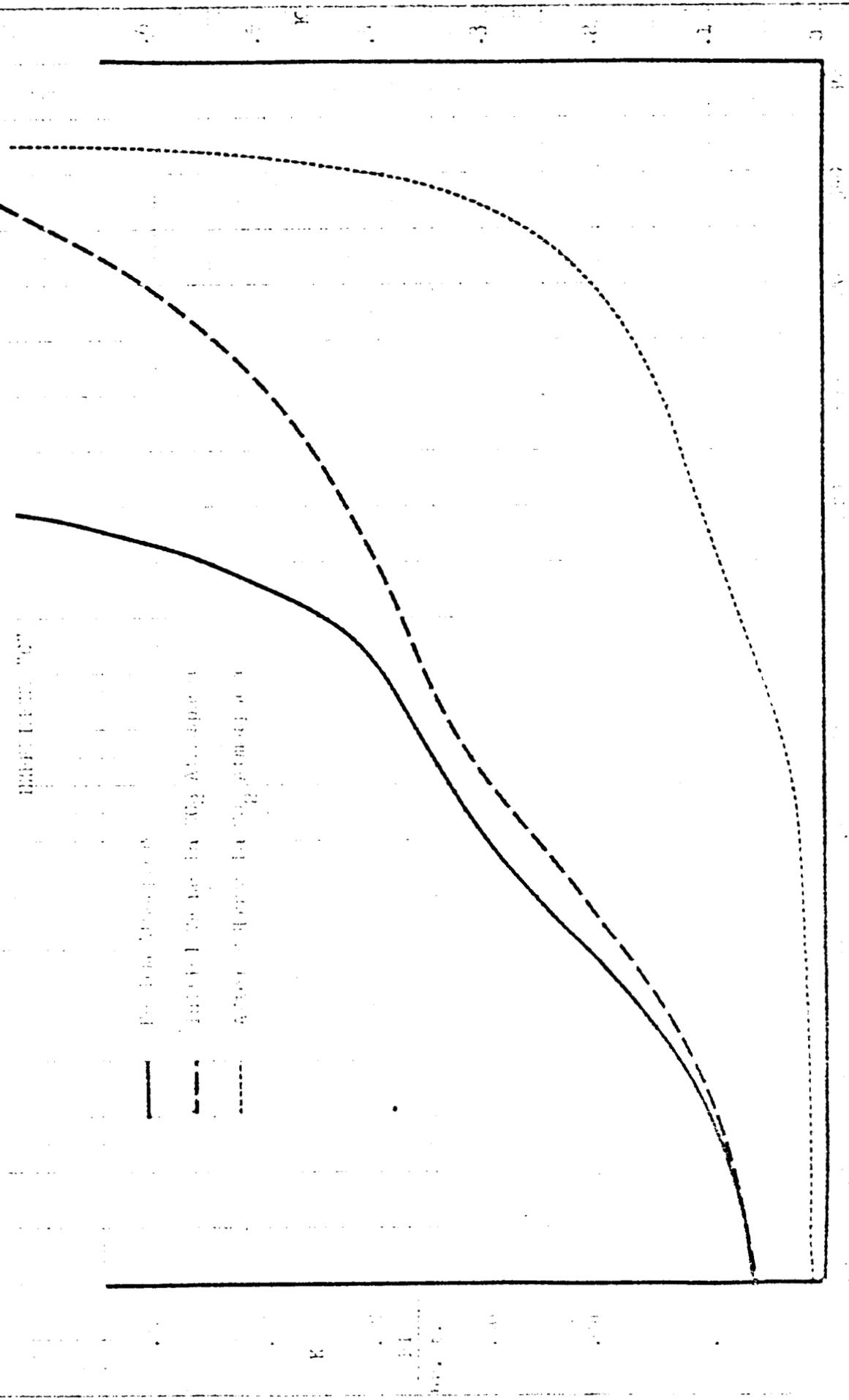
Figure 1

EXPERIMENT "C"

This experiment is identical to "B" with the following exceptions. The volume of the frost was measured by placing the CO₂ frost with a thin sharp metal blade and step No. 12 was taken prior to reaching 350°R. A plot of the thermal conductivity as a function of temperature is given in Figure 6 and additional data is listed below.

Test Procedure Step No.	6	12	12
Thermal Conductivity (Btu)/(hr)(ft)(°R)	.0586	.0655	.114
Warm Temperature (°R)	142.	334.	340.
Cold Temperature (°R)	149.	139.	149.
Density (lbs/ft ³)	30.4	30.4	67.8
Atmosphere	He	CO ₂	CO ₂
Initial Rate of Cryopumping (SCFH/ft ²)	-	1.36	-
Final Rate of Cryopumping (SCFH/ft ²)	-	-	3.77
Chamber Wall Temperature (°F)	63.	121.	196.
CO ₂ Frost Thickness (Inches)	.656	.656	.75

RELATIONSHIP BETWEEN PERMEABILITY AND AVERAGE OF THE
DIFFERENTIAL



RELATIONSHIP BETWEEN PERMEABILITY AND AVERAGE OF THE DIFFERENTIAL

EXPERIMENT "P"

The cryostat was frozen at a rate of 2.15 JPH per square foot of cryogenic tank for a time interval of six hours and no minutes. The cryogenic tank was chilled from 50°F to 15°F over a 3 minute time interval. A plot of the thermal conductivity as a function of temperature is given in Figure 7 and additional data is listed below.

Test Parameters (Steps)

C	H	V
.0333	.122	.0424
419.	390.	390.
130.	130.	130.
22.8	24.8	31
He	CO ₂	He
-	23°	-
-	-	1.9
15.	102.	153.
.005	.005	.005

- Thermal Conductivity (BTU²/hr)(ft)(°R)
- Warm Temperature (°F)
- Cold Temperature (°R)
- Density (lb./ft³)
- Atmosphere
- Initial Rate of Cryopumping (JPH/ft²)
- Final Rate of Cryopumping (JPH/ft²)
- Chamber Wall Temperature (°F)
- CO₂ Frost Thickness (Inches)

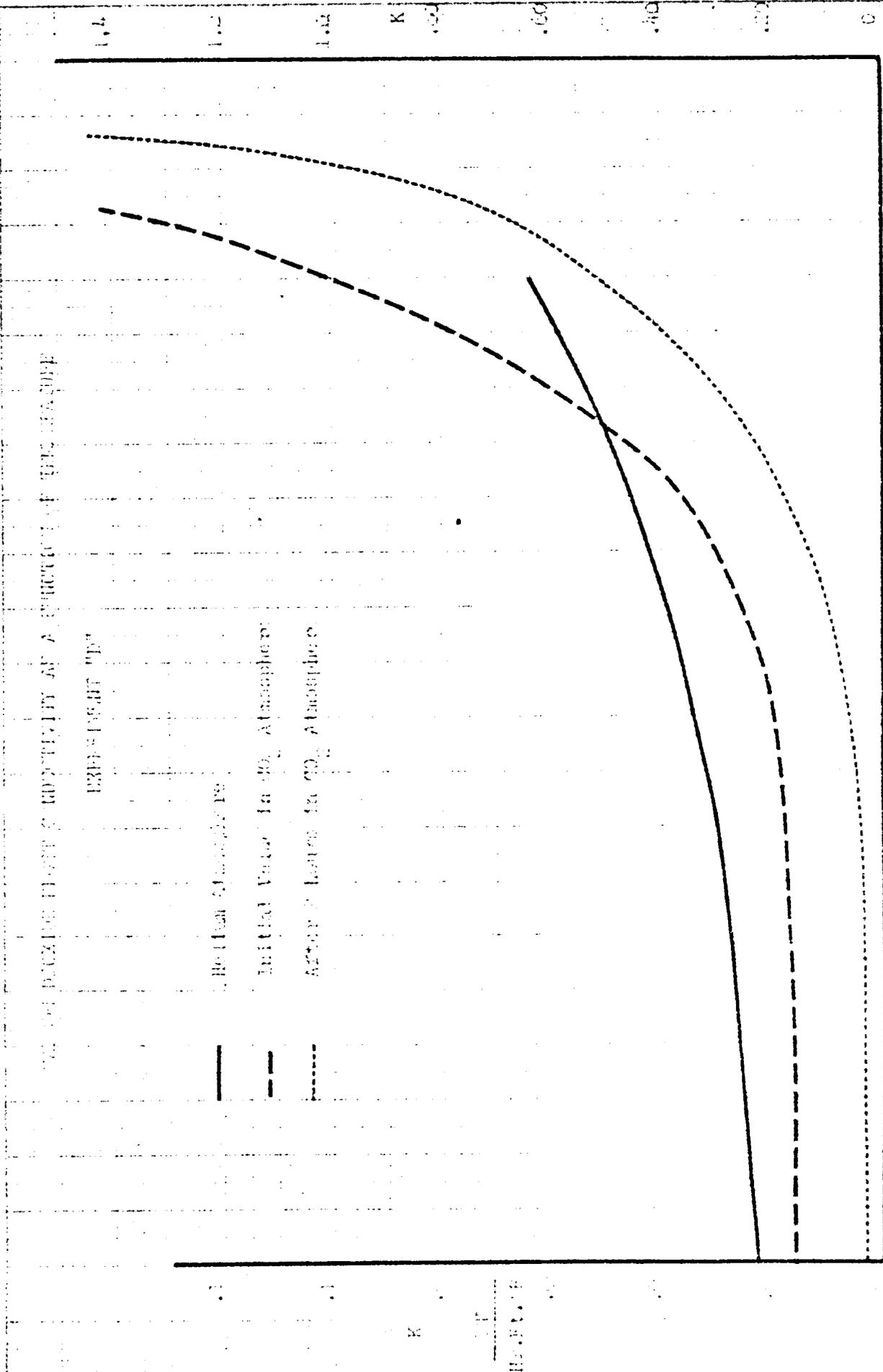
PERCENTAGE DECREASE IN RADIATION AT A CERTAIN DEPTH OF THE LEAF

EXPERIMENT 117

Bottom Chamber

Initial Value In CO_2 Atmosphere

After 2 Hours In CO_2 Atmosphere



EXPERIMENT "E"

The dry frost was frozen at a rate of 2.53 SCFH per square foot of cryogenic tank for a time interval of six hours and 10 minutes. The cryogenic tank was chilled from 350°K over a 120 minute time interval. A plot of the thermal conductivity as a function of temperature is given in Figure 8 and additional data is listed below. In step No. 22 of the test procedure, the helium was vacuum purged from the 0.7% frost and back filled with 0%.

Test Procedure Step No.

	6	12	12
Thermal Conductivity (W/m ²)/(hr)(ft ²)(°K)	.0491	.0223	.0147
Warm Temperature (°K)	273.	347.	250.
Cold Temperature (°K)	139.	139.	137.
Density (lb./ft ³)	27.3	27.3	48.6
Atmosphere	He	0%	0%
Initial Rate of Cryopumping (SCFH/ft ²)	-	6.8	-
Final Rate of Cryopumping (SCFH/ft ²)	-	-	5.8
Chamber Wall Temperature (°F)	32.	87.	138.
0.7% Frost Thickness (Inches)	.025	.025	.030

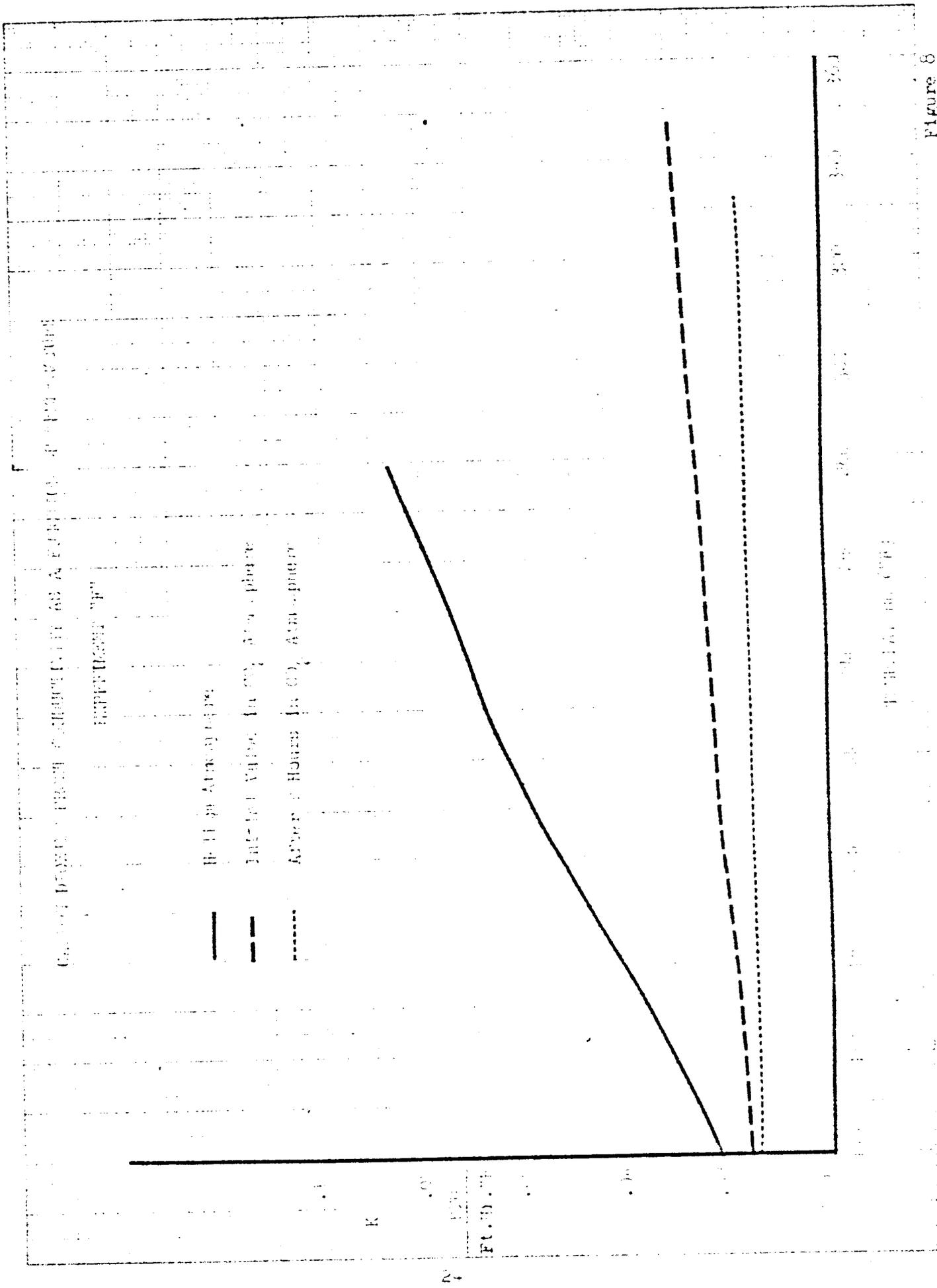


Figure 8

EXPERIMENT "F"

This experiment was identical to "E" with the exception that the cryogenic tank was chilled from 50°R to 1-2°R over a thirty (30) minute time interval. A plot of the thermal conductivity as a function of temperature is given in Figure 9 and additional data is listed below.

Test Procedure Step No.	9	12	13
Thermal Conductivity (GPH)/(hr)(ft)(°R)	.0595	.0314	.0026
Warm Temperature (°R)	302.	450.	300.
Cold Temperature (°R)	139.	139.	139.
Density (lbs/ft ³)	27.1	27.1	27.3
Atmosphere	He	He	He
Initial Rate of Cryopumping (GPH/ft ²)	-	6.8	5.8
Final Rate of Cryopumping (GPH/ft ²)	-	-	182.
Chamber Wall Temperature (°R)	54.	113.	182.
CO ₂ Frost Thickness (Inches)	.625	.625	.625

CONDUCTIVITY OF ADHESIVES AS A FUNCTION OF TEMPERATURE

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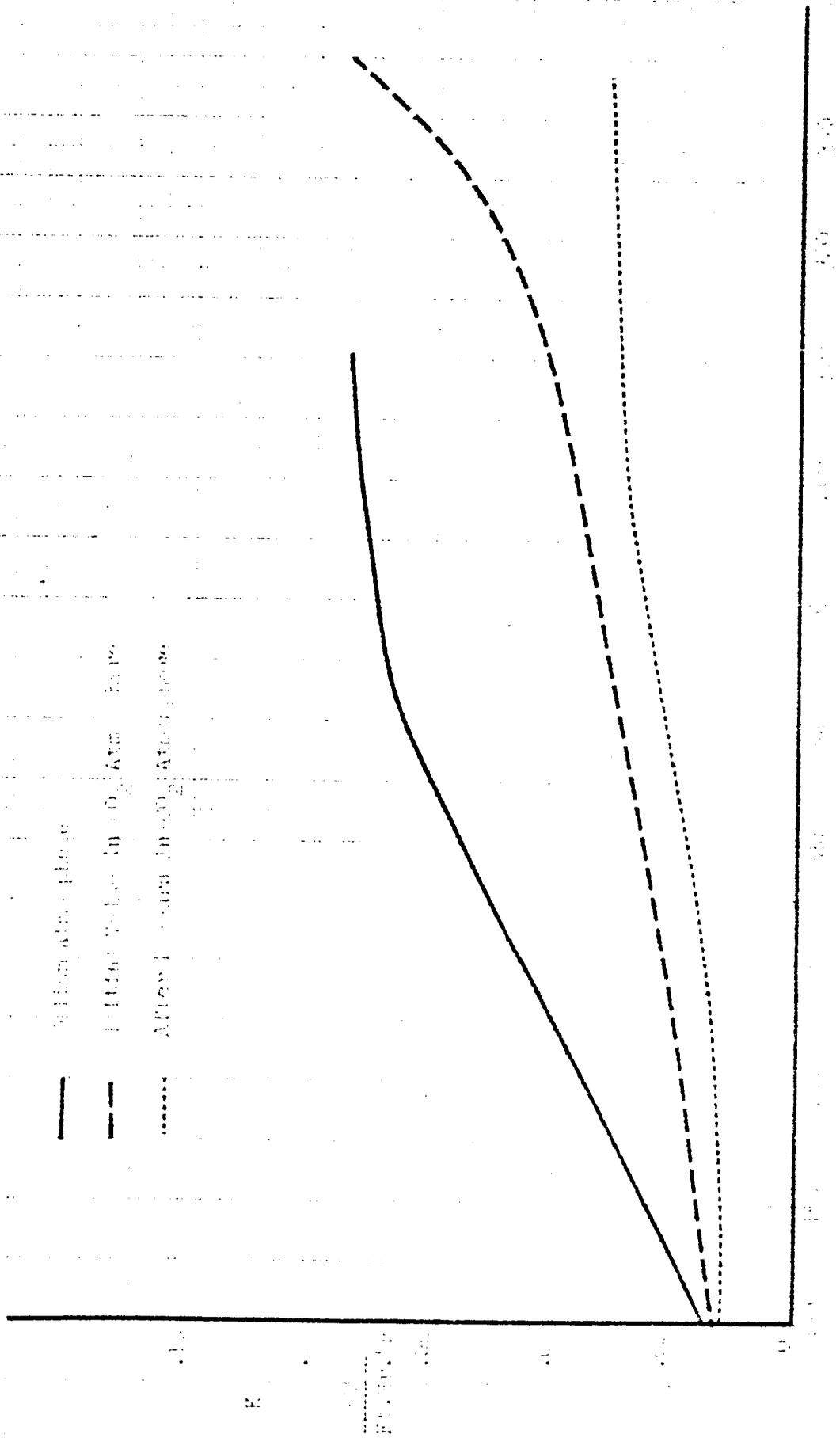


FIGURE 1

EXPERIMENT "G"

The cryofrost was frozen at a rate of $2.1^{\circ}\text{C}/\text{min}$ per square foot of cryogenic tank for a time period of approximately sixteen (16) hours. Diffusivity was encountered in centering the tank floor which resulted in a rapid chilldown of the cryogenic tank and premature termination of the experiment. The experiment was terminated with step number six of the test procedure. At the close of the experiment, the helium was partially purged from the system with dry nitrogen gas to determine if H_2 would be cryopumped through the cryofrost. It was noted that H_2 was slowly cryopumped but no quantitative data was obtained due to time, purity of the H_2 atmosphere and the small quantity of H_2 within the chamber. A plot of the thermal conductivity as a function of temperature is given in Figure 10 and additional data is listed below.

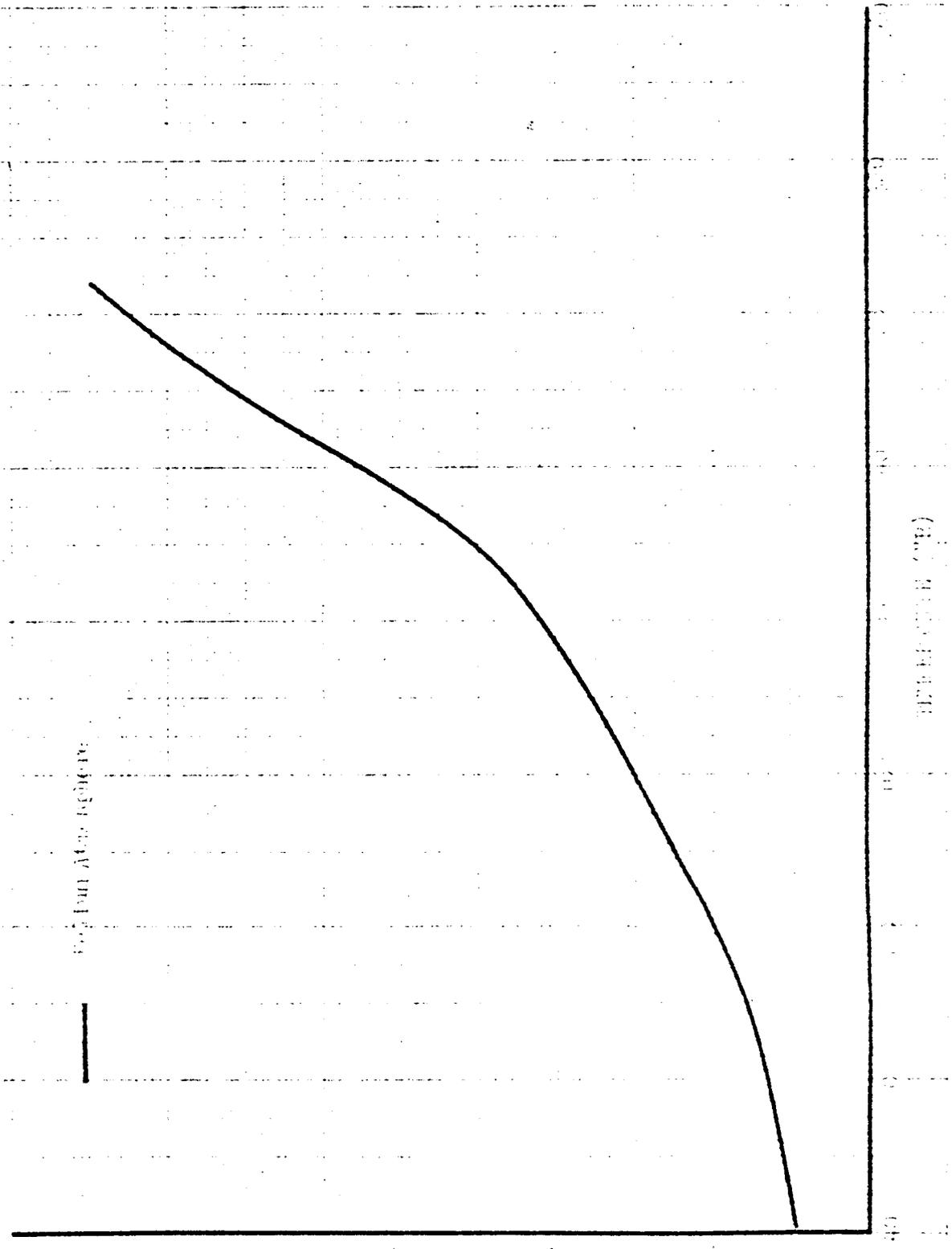
Test Procedure Step 10.

Thermal Conductivity (BTU)/(hr)(ft)($^{\circ}\text{R}$)	.038
Warm Temperature ($^{\circ}\text{R}$)	285.
Cold Temperature ($^{\circ}\text{K}$)	58.
Density (lbs./ft. 3)	31.
Atmosphere	He
CO_2 Frost Thickness (Inches)	.655

CARBON DIOXIDE SPECIFIC CONDUCTIVITY AS A FUNCTION OF TEMPERATURE

EXPERIMENTAL

5.000 Mm. Square



EXPERIMENT "H"

The experiment was identical to "E" and "F" with the exceptions noted below. The cryogenic tanks were chilled from 30°K to 15°K over a sixty (60) minute time interval and the test procedure was followed only through step No. 6. Following step No. 6, gaseous CO₂ was injected into the system at approximately 10.5BPH per square foot of cryogenic tank in an effort to flush purge the helium from the CO₂ frost. After an hour had lapsed, the heat flux through the CO₂ frost was measured. A plot of the thermal conductivity as a function of temperature is given in Figure 11 and additional data is listed below.

Test Procedure Step No.

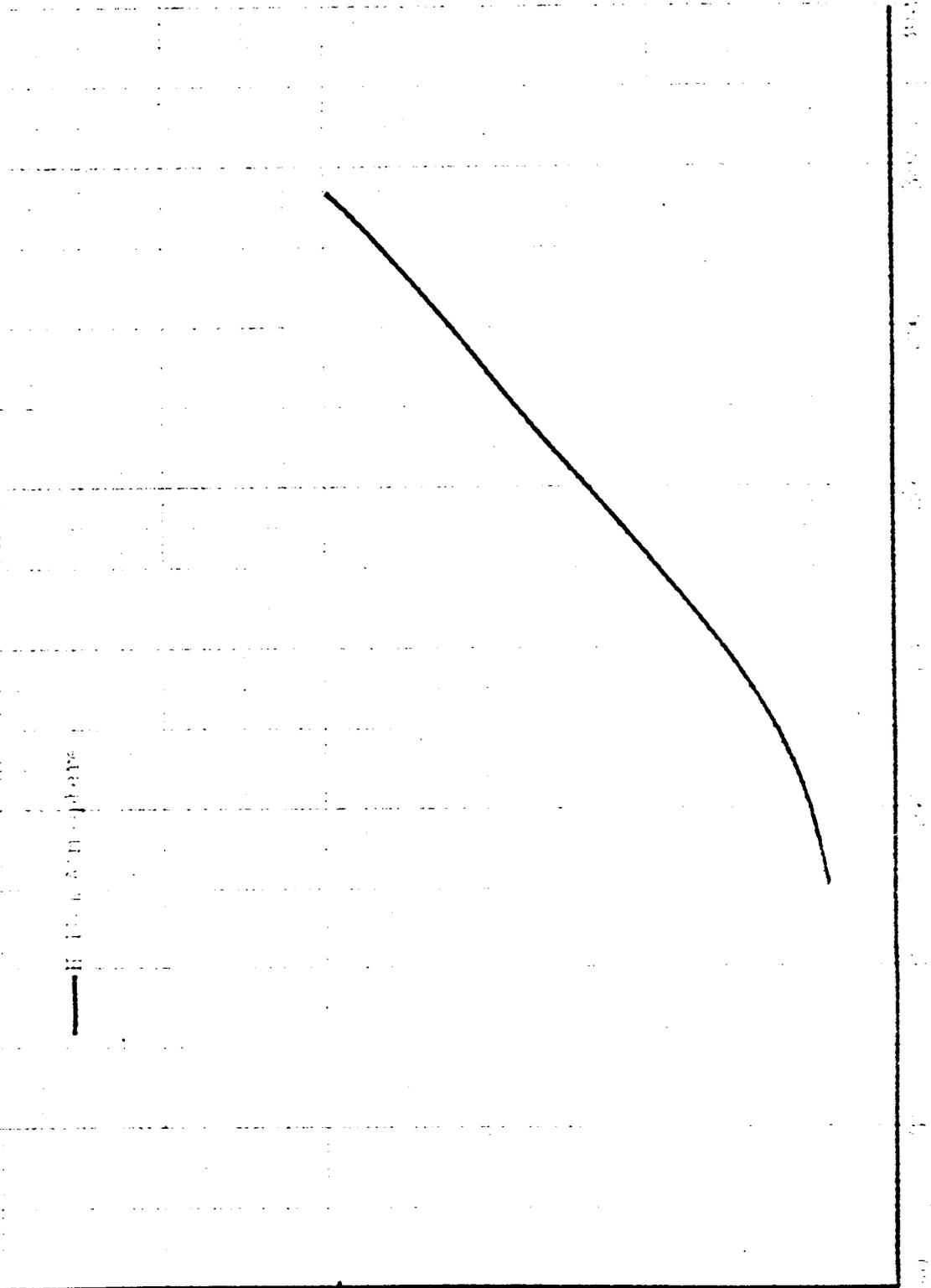
6 X

Thermal Conductivity (BTU)/(hr)(ft)(°R)	.0432	.123
Warm Temperature (°R)	305.	350.
Cold Temperature (°R)	139.	139.
Density (lb./ft. ³)	27.3	37.1
Atmosphere	He	CO ₂
CO ₂ Frost Thickness (Inches)	.625.	.91

COMPARISON OF COMPUTED AND EXPERIMENTAL RESULTS

EXPERIMENTAL DATA

— 10.0 KIN. THEORY



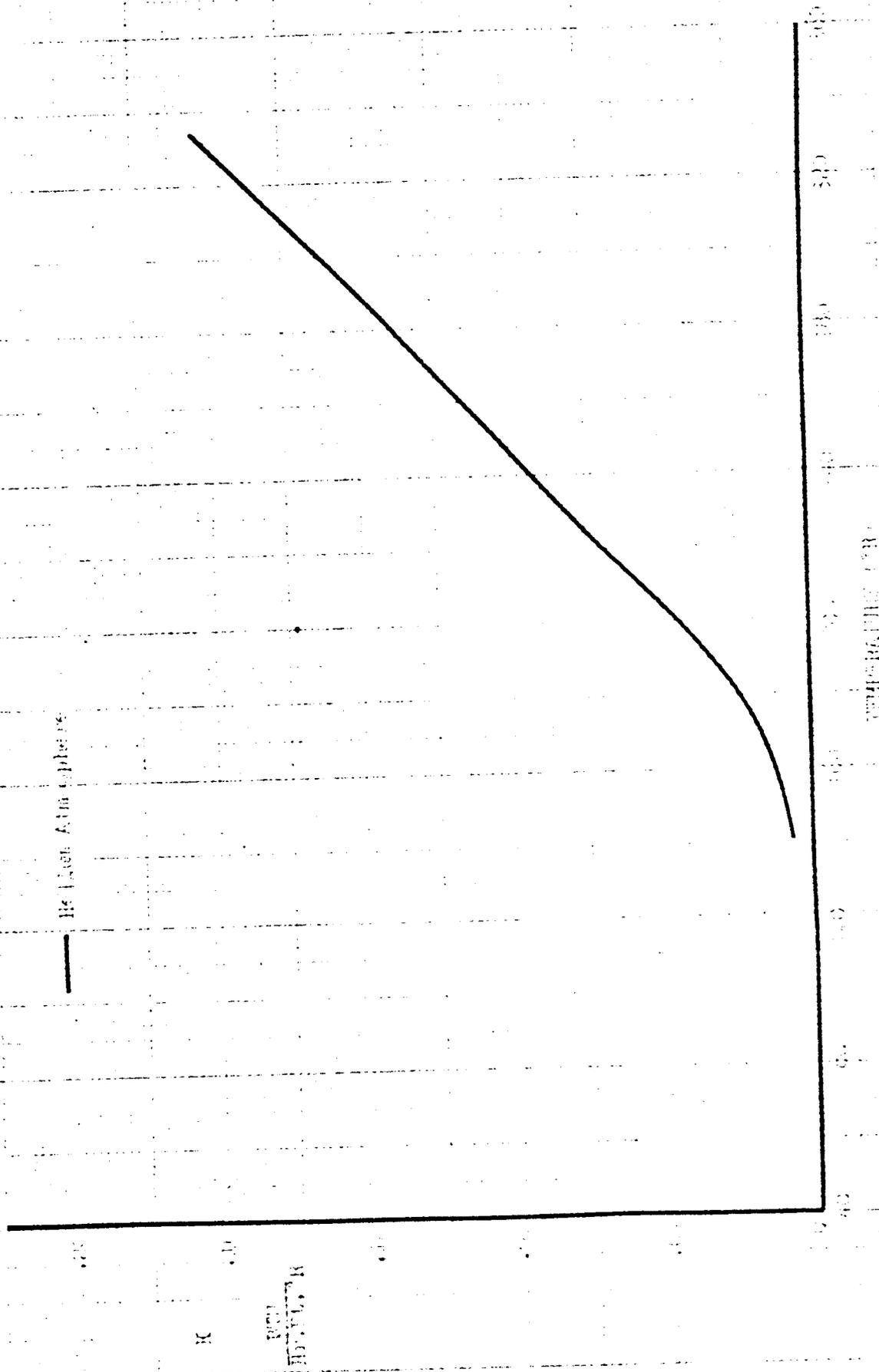
EXPERIMENT "1"

This experiment was the same as "D" with the following exceptions. The cryogenic tank was chilled from 5°K to 1.9°K over a 120. minute time interval and the experiment was terminated with step 10. 7 of the test procedure. A plot of the thermal conductivity as a function of temperature is given in Figure 12 and additional data is listed below.

Test Procedure Step 10.

Thermal Conductivity (KFT)/(hr)(ft)(°K)	.076
Warm Temperature (°K)	.337
Cold Temperature (°K)	1.9
Density (lb./ft ³)	22.7
Atmosphere	He
Gap, Front Thickness (inches)	.62 ave

OXIDE FILM CONDUCTIVITY AS A FUNCTION OF TEMPERATURE
 EXPERIMENT



1/10

EXPERIMENT "J"

This experiment was the same as "I" with the following exception. The cryogenic tank was chilled from 350°R to 130°R over a sixty (60.) minute time interval. A plot of the thermal conductivity as a function of temperature is given in Figure 13 and additional data is listed below.

Test Procedure Step No.

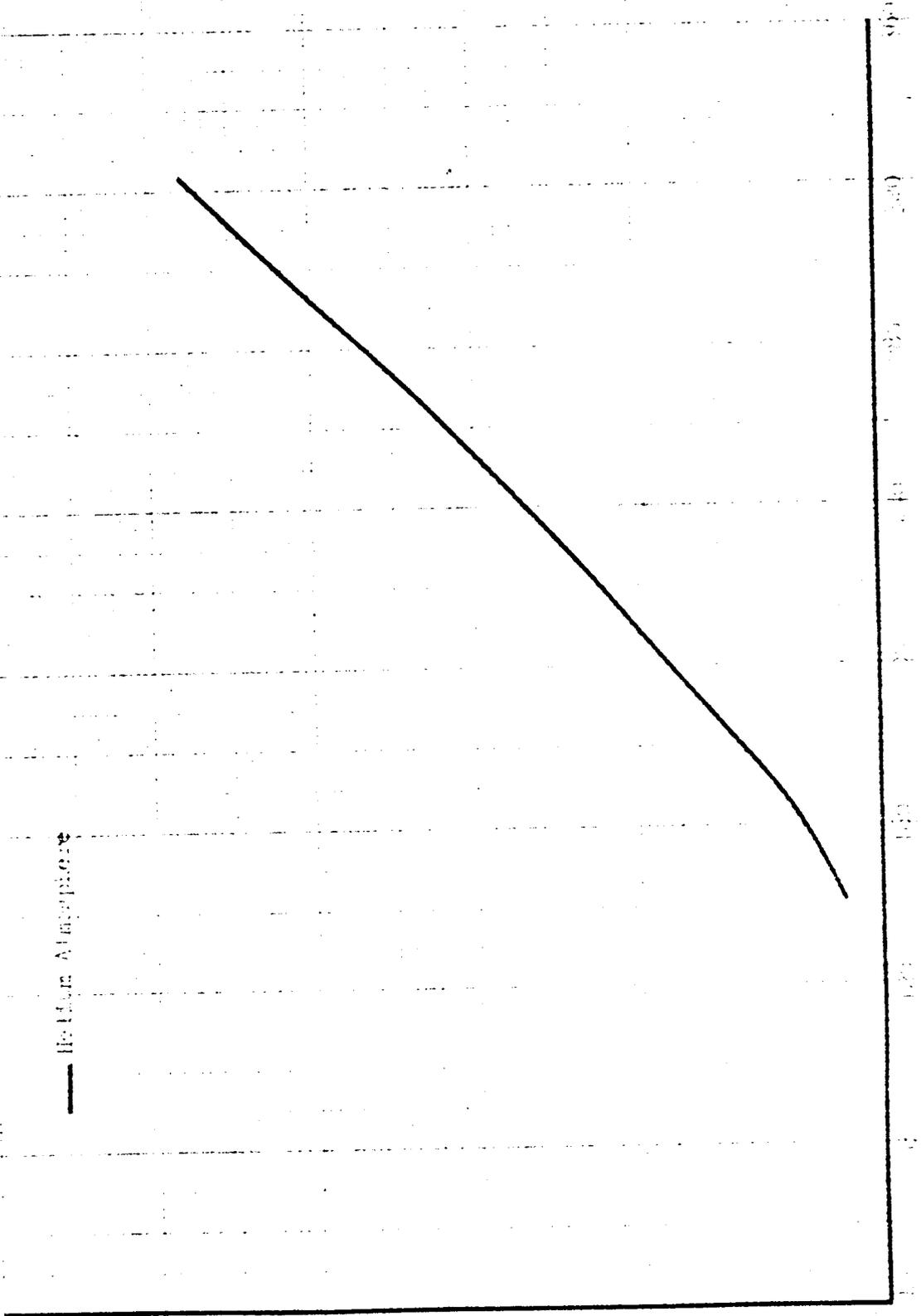
X

Thermal Conductivity (BTU)/(hr)(ft)(°R)	.0477	.0694
Warm Temperature (°R)	350. est.	350. est.
Cold Temperature (°R)	130.	130.
Density (lbs/ft. ³)	22.8	24.5
Atmosphere	He	CO ₂
CO ₂ Frost Thickness (Inches)	.02 ave	.62 ave

CARBON DIOXIDE FLEET CONCENTRATION AS A FUNCTION OF TEMPERATURE

EXPERIMENT "A"

Helium Atmosphere



EXPERIMENT "K"

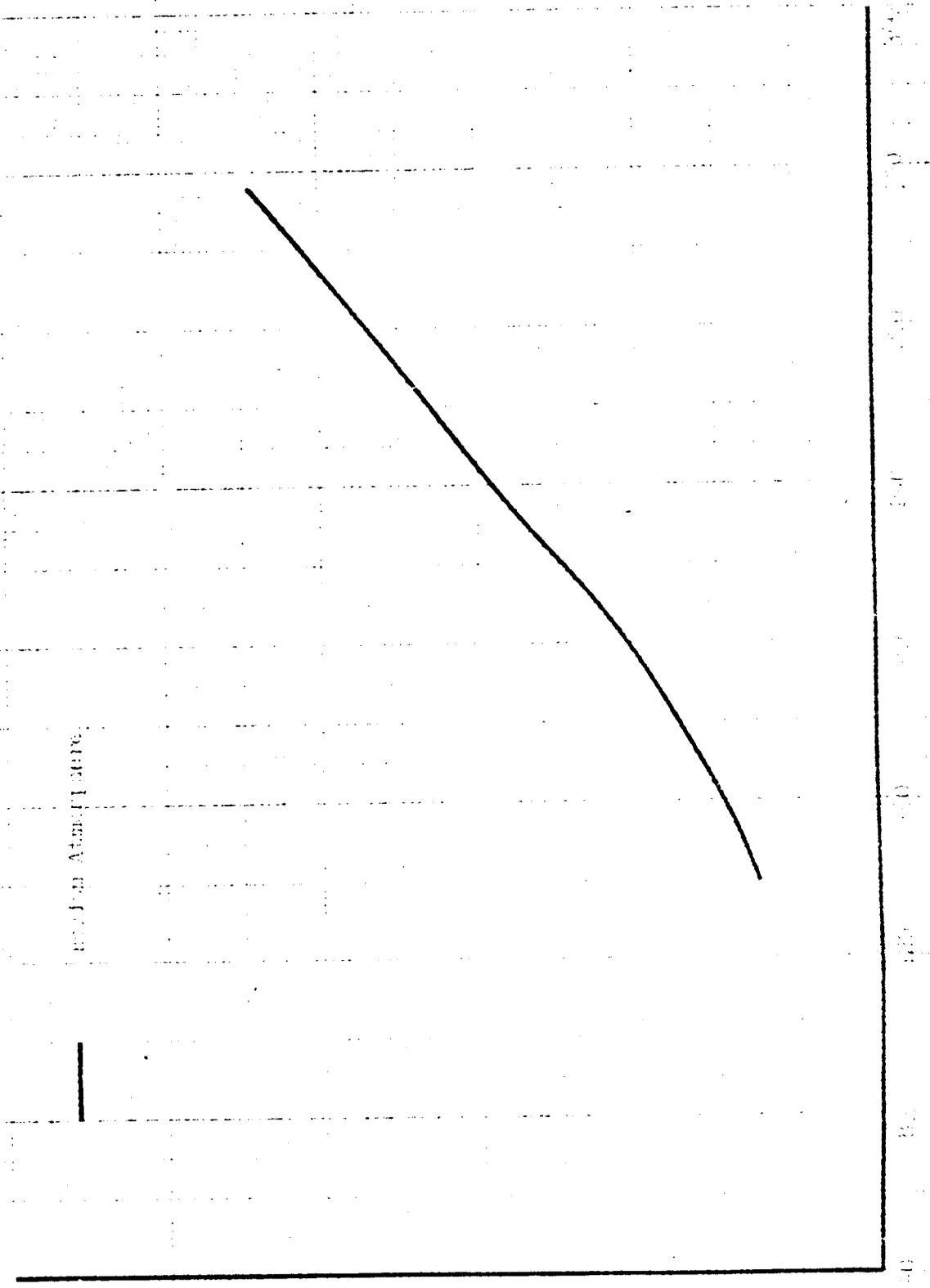
The CO₂ frost was frozen at a rate of 2.15 SCFH per square foot of cryogenic tank for approximately 20 hours. The experiment was terminated with step No. 7 of the test procedure. The insulation was kept at four inches of water gauge pressure and helium was subjected with the CO₂ at a rate of eleven SCFH. A plot of the thermal conductivity as a function of temperature is given in Figure 14 and additional data is listed below.

Test Procedure Step No.

6

Thermal Conductivity (RTU)/(hr)(ft)(°R)	.0221
Warm Temperature (°R)	317.
Cold Temperature (°R)	139.
Density (lbs/ft ³)	50.9
Atmosphere	He
CO ₂ Frost Thickness (Inches)	.083 ave

CARDIOPROTECTIVE EFFECTS OF PROPRANOLOL AS A FUNCTION OF THE HEART RATE
RESPONSE (%)



EXPERIMENT "L"

The CO₂ frost was frozen at a rate of 1.65 SCFH per square foot of cryogenic tank for approximately thirty five hours. The experiment was terminated with step No. 7 of the test procedure. The insulation was kept at four inches of water gauge pressure and helium was injected with the CO₂ at a rate of eleven SCFH. A plot of the thermal conductivity as a function of temperature is given in Figure 15 and additional data is listed below.

Test Procedure Step No.

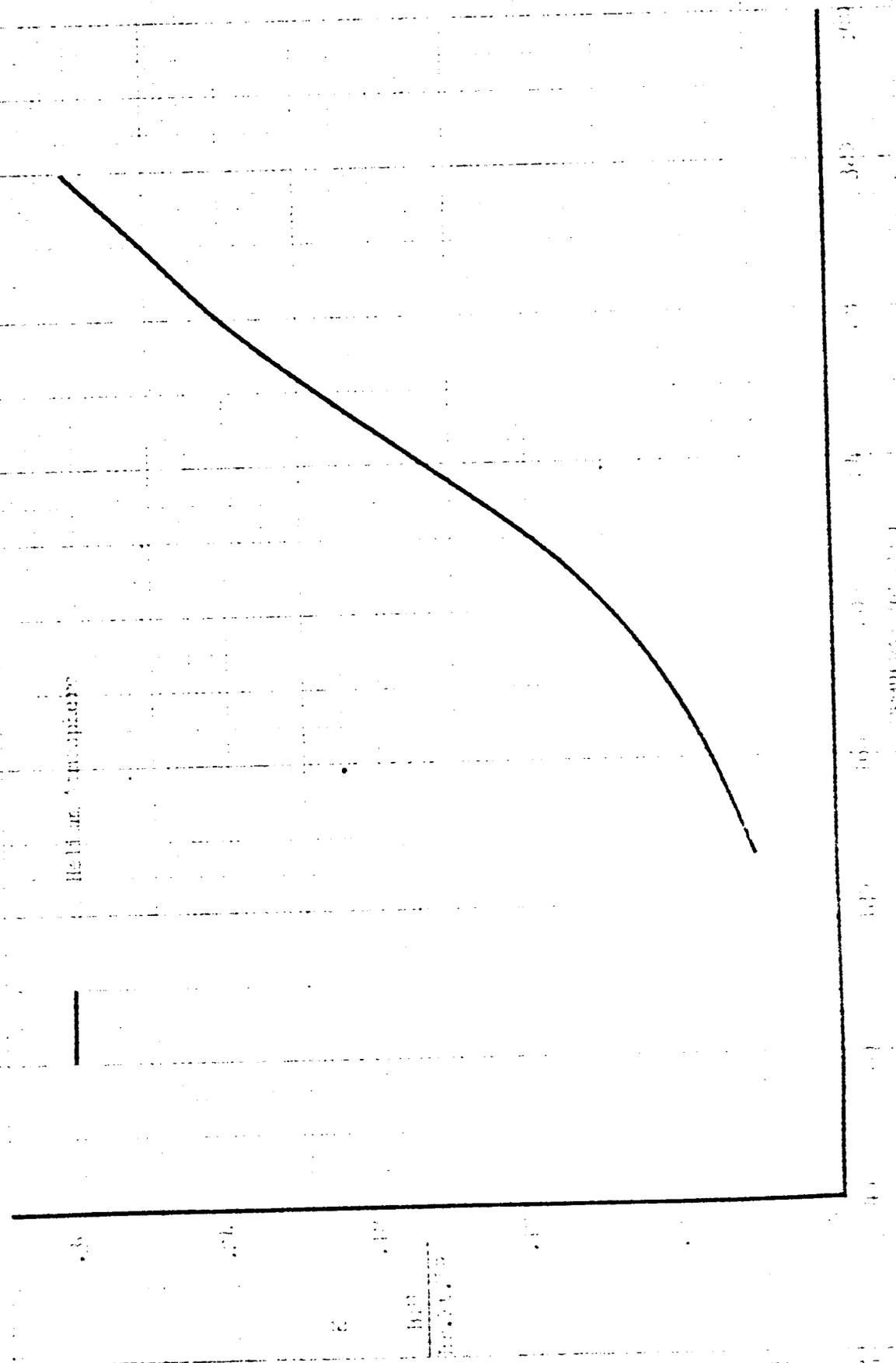
6

Thermal Conductivity (BTU)/(hr)(ft)(°F)	.136
Warm Temperature (°F)	532.
Cold Temperature (°R)	139.
Density (lb/ft ³)	59.8
Atmosphere	He
CO ₂ Frost Thickness (inches)	1.05

CAPACITY FACTOR PRODUCTIVITY AS A FUNCTION OF TEMPERATURE

EXPERIMENT "1"

held at atmosphere



EXPERIMENT "M"

The dry frost was frozen at a rate of 0.8 SCFH per square foot of cryogenic tank and increased at a constant rate to 5.6 SCFH per square foot of cryogenic tank at the end of the experiment. The insulation was kept at four inches of water gauge pressure and helium was injected with the CO₂ at a rate of eleven SCFH. The CO₂ was frozen for a period of 7.5 hours. Following step No. 7 of the test procedure, the He₂ was replaced with He₁ as the heat sink and the helium was purged from the insulation with dry nitrogen. The heat flux and temperature distribution through the frost was measured and it was observed that the He₂ was being cryopumped. The rate at which the He₂ was being cryopumped was not measured, but it was approximately 1.8 SCFH per square foot of cryogenic tank. A plot of the thermal conductivity as a function of temperature is given in Figure 16 and additional data is listed below.

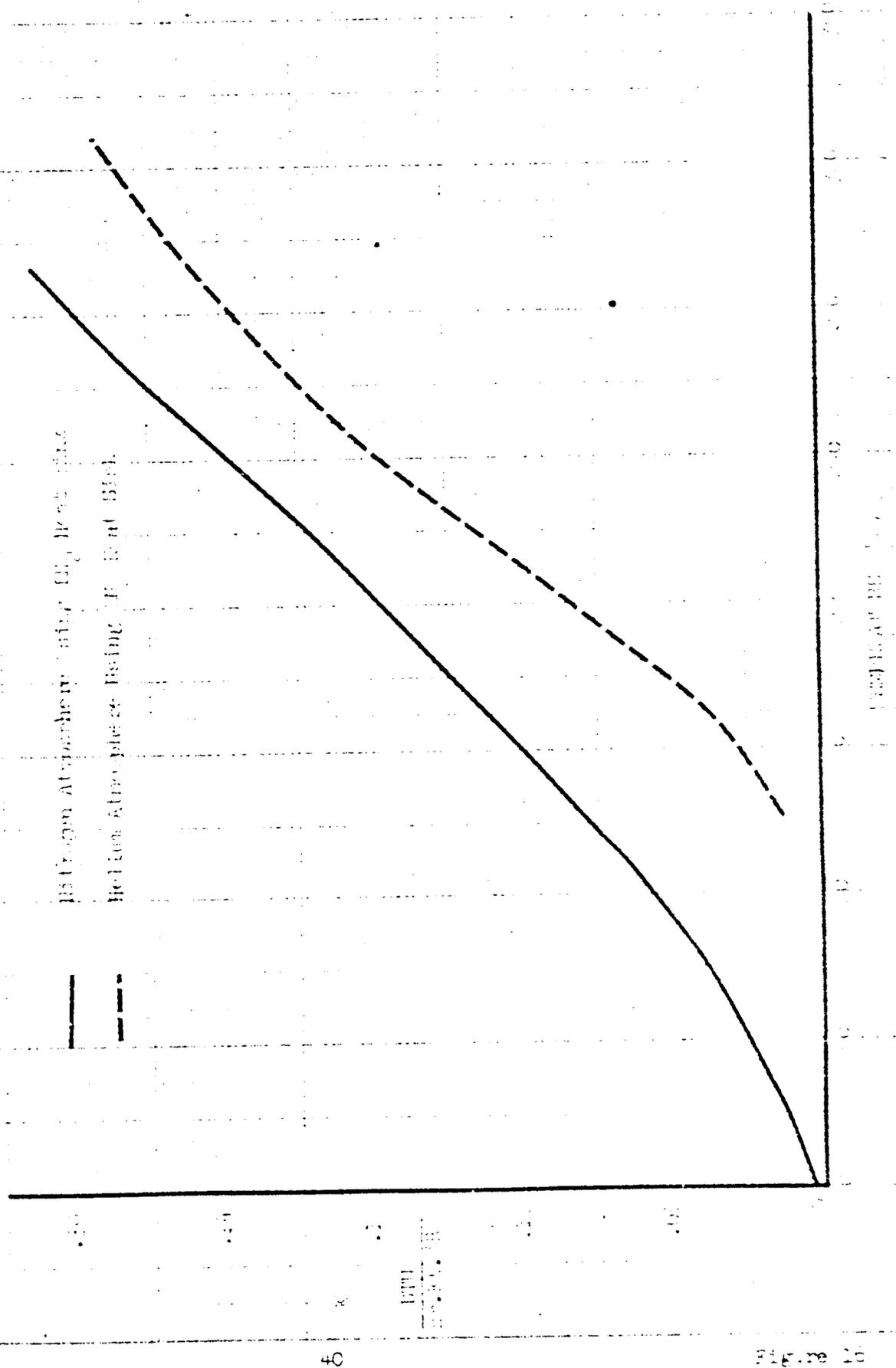
Test Procedure Step No.

X

Thermal Conductivity (BTU)/(hr)(ft)(°R)	.178	.168
Warm Temperature (°R)	490.	490.
Cold Temperature (°K)	153.	43.
Density (lbs/ft ³)	94.3	84.3
Atmosphere	He	He
CO ₂ Frost Thickness (inches)	1.60	1.60

ANION EXCHANGE POLYMER CATIONICITY AS A FUNCTION OF TEMPERATURE

EXPERIMENT 100



ϕ_c

MMA
PERCENTAGE

Fig. 10

EXPERIMENT "H"

This experiment was the same as "M" with the exceptions noted below. The CO₂ frost growth rate was increased linearly from 3.4 to 5.3 SEFH per square foot of cryogenic tank over a twenty hour time interval. The partial pressure of helium within the quartz battery was allowed to fall below one atmosphere which caused the CO₂ frost to grow as a very dense clear ice crystal. Due to non-availability of LiI₂, the experiment was terminated with step 15. 7 of the test procedure. A plot of the thermal conductivity as a function of temperature is given in Figure 17 and additional data is listed below.

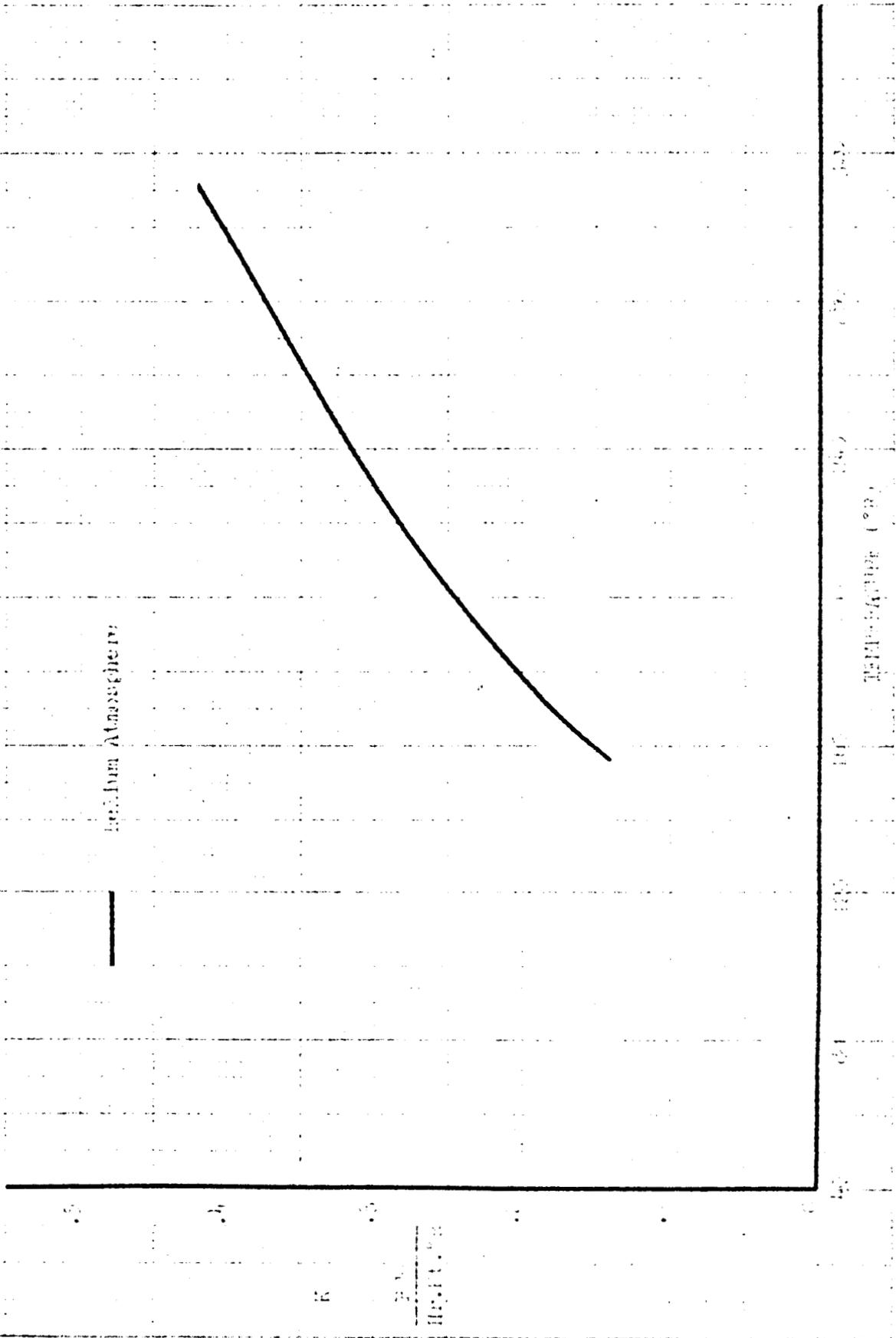
Test Procedure Step No.

6

Thermal Conductivity (SEFH)/(hr)(ft)(°R)	5.49
Warm Temperature (°R)	323.
Cold Temperature (°R)	139.
Density (lbs./ft ³)	87.5
Atmosphere	He
CO ₂ Frost Thickness (Inches)	1.28

CARBON MONOXIDE LOSS FROM COILS DURING A PERIOD OF TEMPERATURE

EXPERIMENT "D"



EXPERIMENT "O"

This experiment was the same as "E" with the exceptions noted below. The O₂ frost growth rate was measured linearly from 3.0 to 5.5 cmH per square foot of cryogenic tank over a 24 hour time interval. A plot of the thermal conductivity as a function of temperature is given in Figure 18 and additional data is listed below.

Test Procedure Step 12.

	<u>b</u>	<u>K</u>
Thermal Conductivity (BTU)/(hr)(ft)(°R)	.160	.299
Warm Temperature (°K)	350.	285.
Cold Temperature (°R)	139.	38.
Density (lb/ft ³)	77.9	77.9
Atmosphere	He	N ₂
O ₂ Frost Thickness (inches)	1.37	1.37

CARBON DIOXIDE FROM A DEPOSITED AS A FUNCTION OF TEMPERATURE

PERCENTAGE

100% Atmosphere (100% H_2 Gas + 0% CO_2)

20% CO_2 Atmosphere (80% H_2 Gas + 20% CO_2)

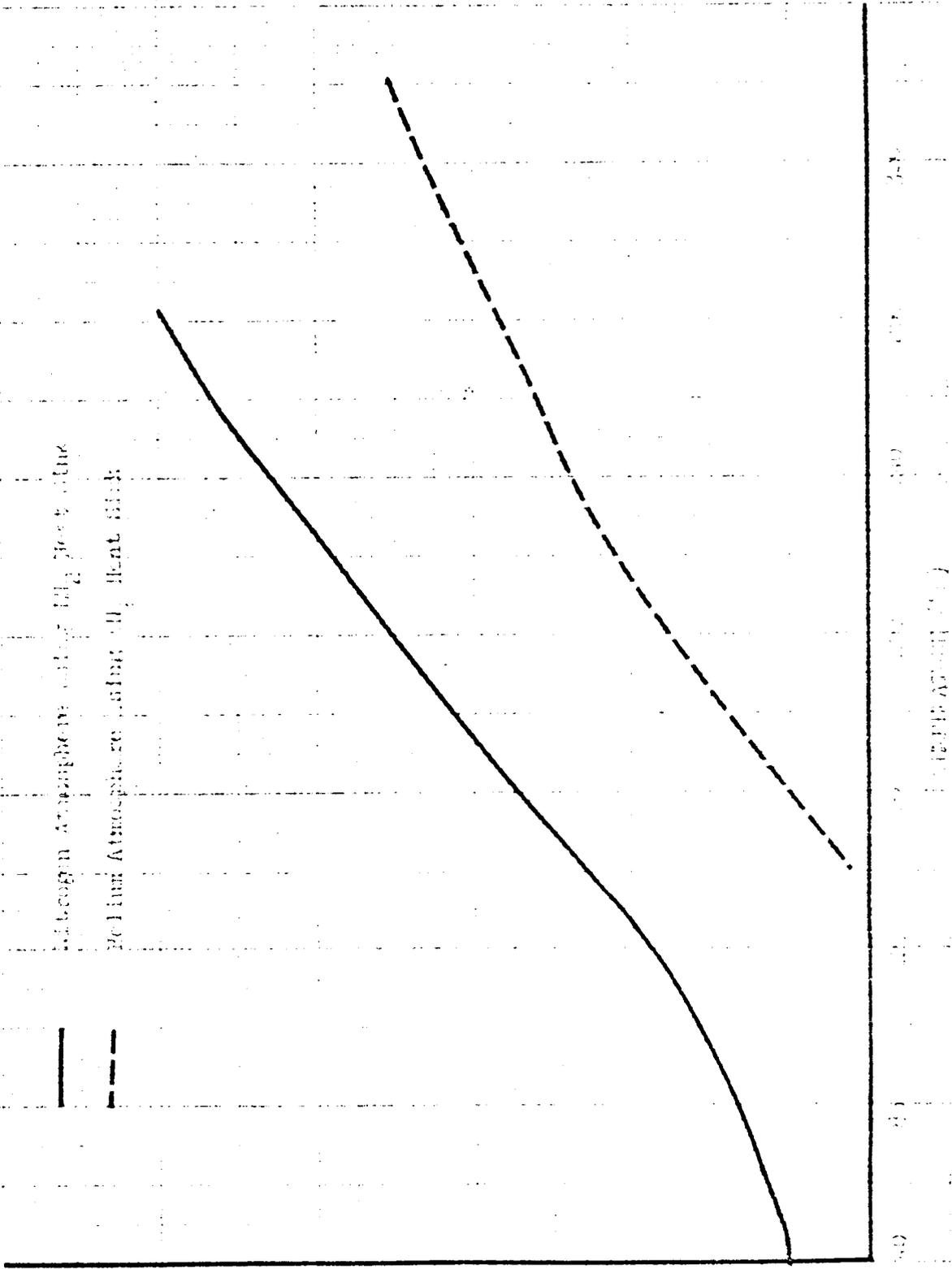


Figure 10

EXPERIMENT "P"

This experiment was the same as "E" with the exceptions noted below. The CO₂ frost growth rate was increased linearly from 4.3 to 6.5 SFPH per square foot of cryogenic tank over a twenty six hour time interval. Liquid Hydrogen was used for a thirty (30.) minute chill from 30°R to 38°R and for the first hour of CO₂ frost build up. The bulk of the frost was formed using IN₂ as the heat sink. A plot of the thermal conductivity as a function of temperature is given in Figure 19 and additional data is listed below.

Test Procedure Step No.

6

X

Thermal Conductivity (BTU)/(hr)(Ft)(°R)	.185	.236
Warm Temperature (°R)	338.	291.
Cold Temperature (°R)	139.	38.
Density (lbs Ft ³)	77.4	77.4
Atmosphere	He	N ₂
CO ₂ Frost Thickness (Inches)	1.4 ave	1.4 ave

COEFFICIENT OF DIFFUSIVITY AS A FUNCTION OF TEMPERATURE

BY BRUCE W. P.

Average Atmospheric Data, 1948-1952
 Station: Columbia, S.C.

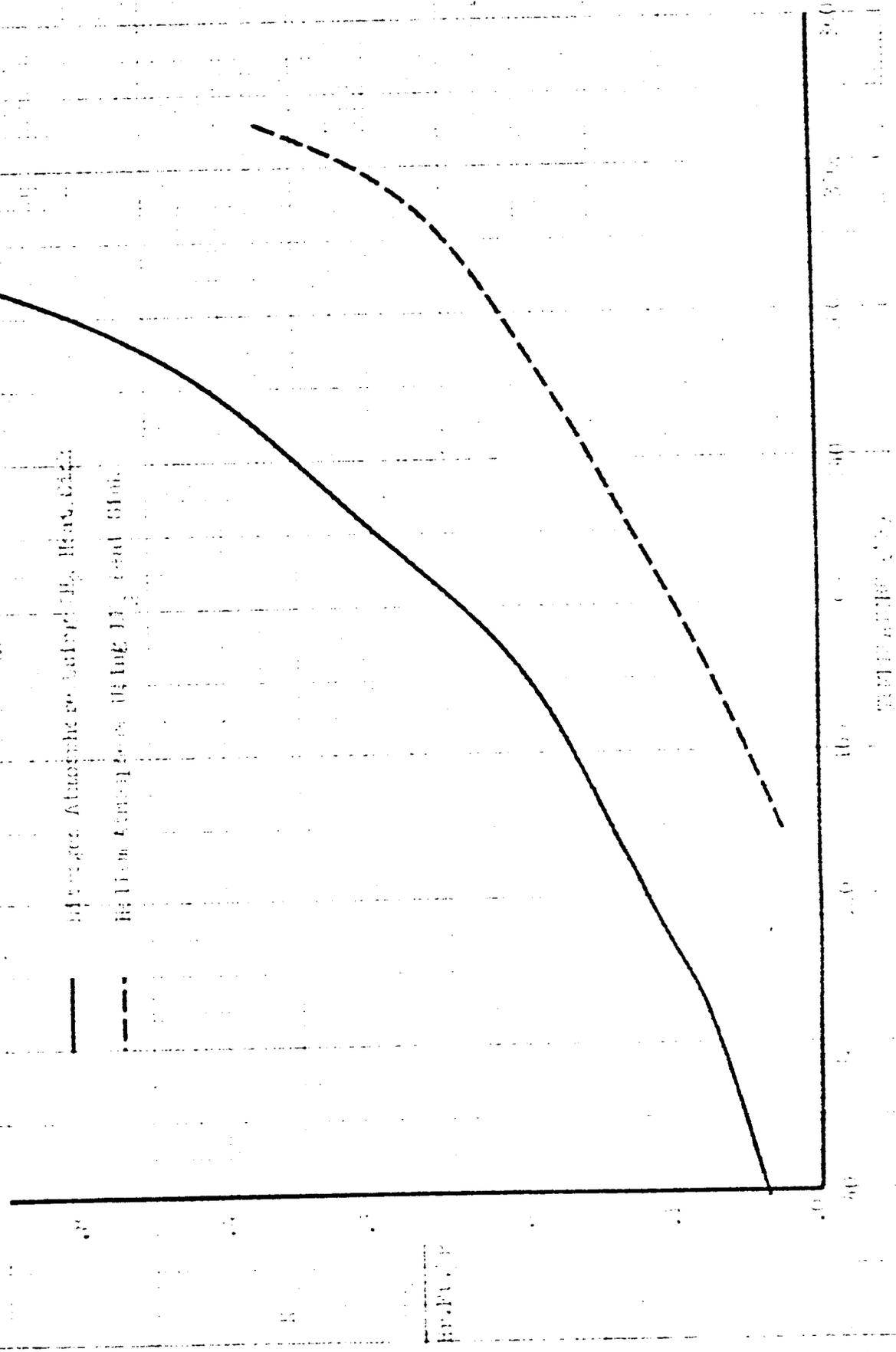


Figure 10

CARBON DIOXIDE FLOW CHARACTERISTICS AS A FUNCTION OF TEMPERATURE

EXPERIMENT NO. 100

Air flow through heated bed
 Air flow through heated bed

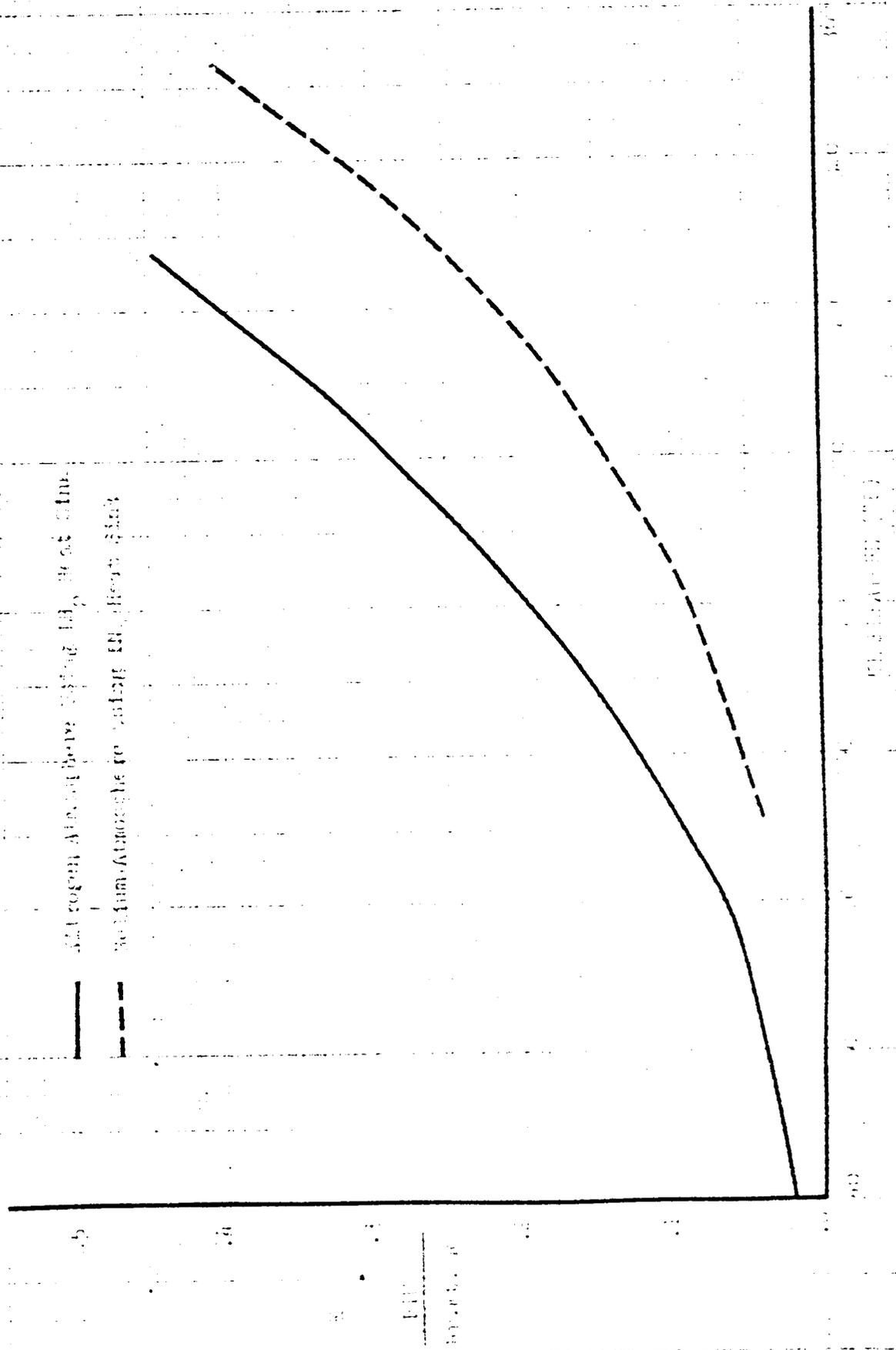


Figure 20

EXPERIMENT "E"

The CO₂ frost was frozen at a rate of 2.0 SUFH per square foot of cryogenic tank for fifty two hours and another fifty hours as a heat sink. At the conclusion of step No. 6 of the test procedure, the test was replaced with LI₂. At this point, steps No. 6 and No. 7 of the test procedure were performed and the experiment was terminated. A plot of the temperature as a function of time is given in Figure 21 and additional data is listed below.

Test Procedure Step No.

6 7

Thermal Conductivity (BTU)/(hr)(ft)(°R)	.0366	.0776
Warm Temperature (°R)	350	345
Cold Temperature (°R)	38	139
Density (lb/ft ³)	2.45	27.5
Atmosphere	He	He
CO ₂ Frost Thickness (inches)	2.15	2.15

TABLES OF THEORETICAL AND EXPERIMENTAL DATA ON THE PROPERTIES OF POLYMERIZATION

EXPERIMENT 4

Plot of $\ln \frac{[M]_0}{[M]}$ vs. t

Plot of $\ln \frac{[M]_0}{[M]}$ vs. t

—

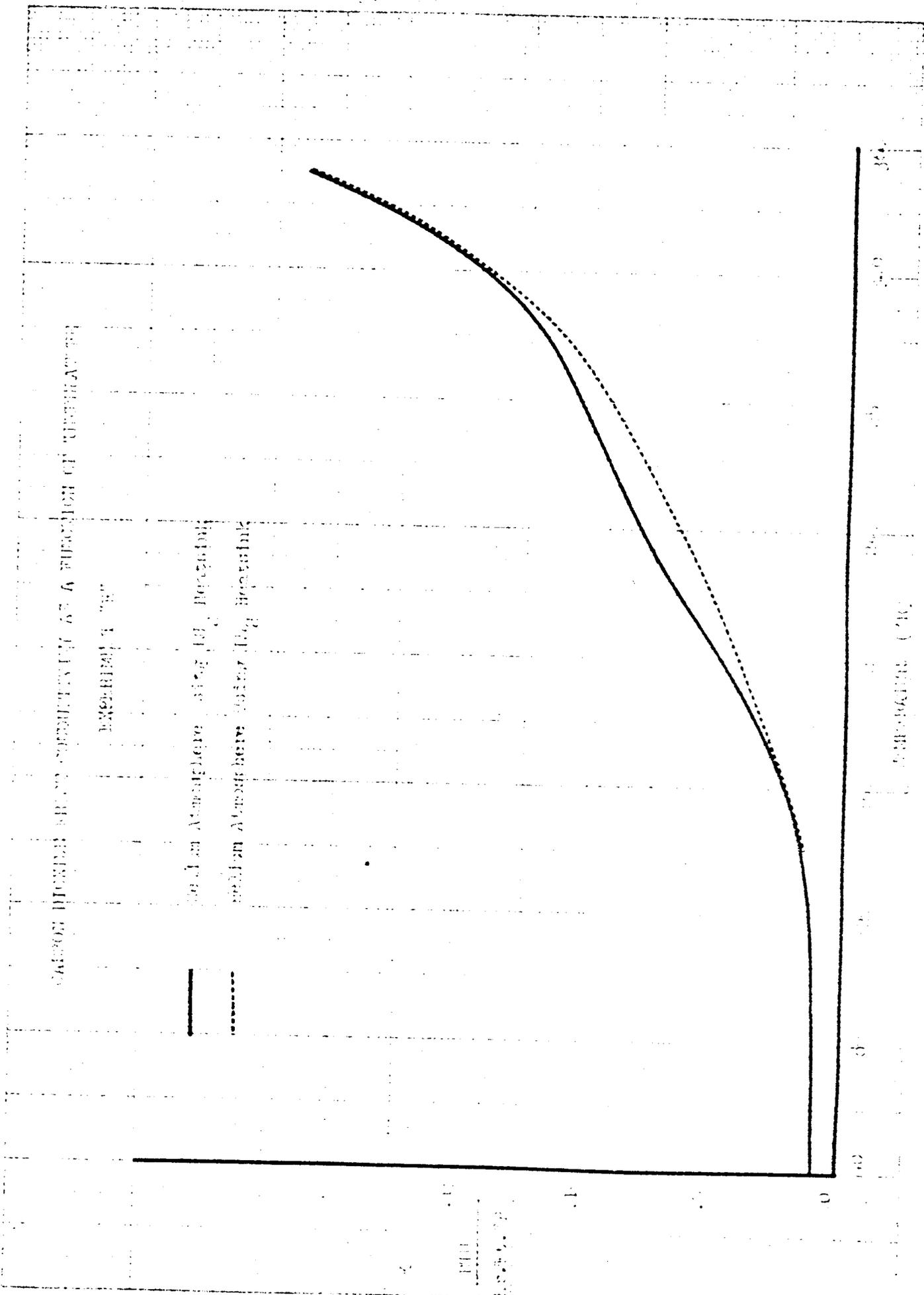


Figure 21

The major source of error in reduction of the experimental data is the frost thickness. The error is two fold, first, is the uniformity of frost on the test cylinder and, second, is the accuracy with which the frost can be measured. The frost thickness was measured photographically and the photograph measured with a scale or measured with calipers and scale directly. The photographs were approximately 1/5 actual size which increased the error inherent in a scale by a factor of five. The worn metal calipers contained a small quantity of O_2 directly beneath them which made the readings slightly small.

The non-uniformity of the ice is a major problem as the thermal conductivity of a given frost specimen is a function of position and temperature as demonstrated in Figure 5. To reduce the data, one must determine the radius of a perfect hollow cylinder of O_2 frost which would give the same thermal results as the existing experimental ice growth.

The shape of the O_2 frost crystals reported on in this paper are illustrated in Figures 20, 22 and 23. Figure 20 is representative of experiments "A" through "E". In these experiments, the O_2 was injected into the vacuum chamber from a single point, two inches below and ten inches from the top of the upper cylindrical tank. The O_2 was dispersed by gravity and gaseous diffusion which created an inverted truncated cone with a total change of .125 inches in diameter in the fifty two inch length. Figure 22 is representative of experiments "G" through "I". In these experiments, the O_2 was injected into the vacuum chamber six inches from the oxygenic cylinders at

FIGURE 22. - CO₂ FROST GROWTH

REPRESENTATIVE OF EXPERIMENTS "G" - "J"

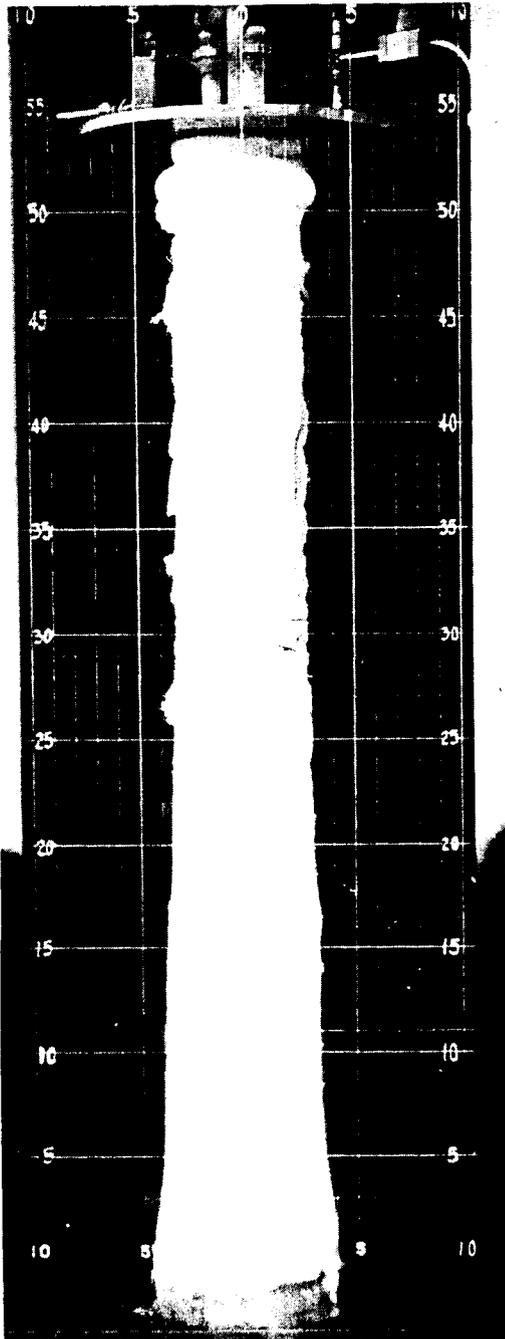
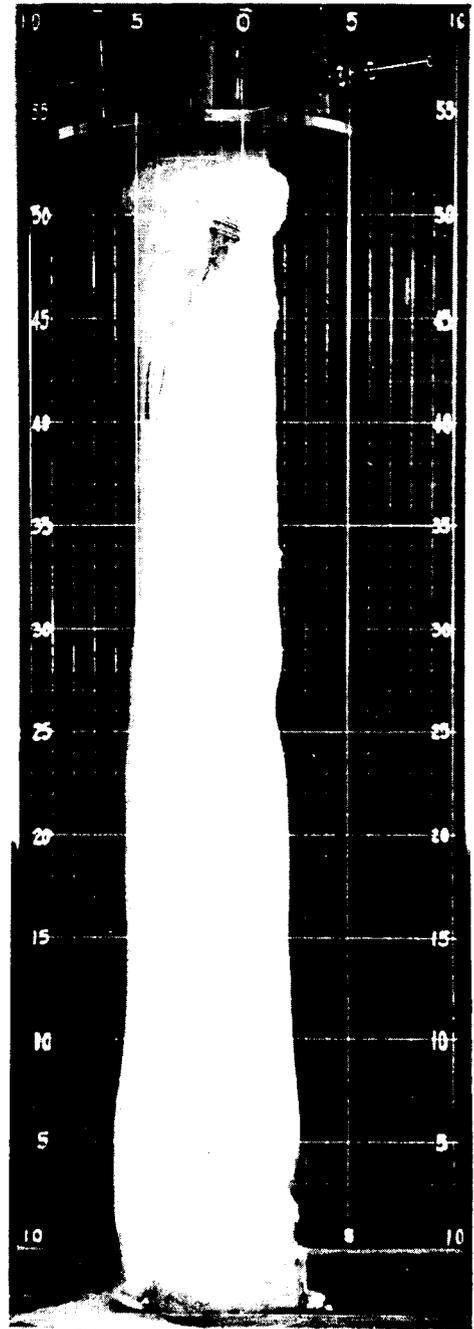


FIGURE 23. - CO₂ FROST GROWTH

REPRESENTATIVE OF EXPERIMENTS "K" - "R"



spaced intervals along the entire length, for the first two hours, and from a single point near the top for four hours. These CO_2 frost growths changed as much as .5 inches in diameter on the sixteen inch test tank and were irregular in shape. Figure 23 is representative of experiments "K" through "E". In these experiments, CO_2 or SO_2 and helium were injected into the vacuum chamber at a fixed rate and excess gas was vented at the top to keep the insulation atmosphere at 15. psia. The gas was injected in a variety of locations ranging from "at the bottom only" to "equally spaced points along the length". The shape of this CO_2 frost specimen can be seen from the illustration.

The effect of the "measured frost thickness" on the experimental results is illustrated in the following example. If the CO_2 frost thickness of experiment "F" were reduced by .17 inch, the density would be raised from 27.3 to 31.4 lbs/ft³ and the thermal conductivity lowered from .0021 to .0014 BTU/HR FT² °F for an 18.7% decrease and a .7% increase respectively.

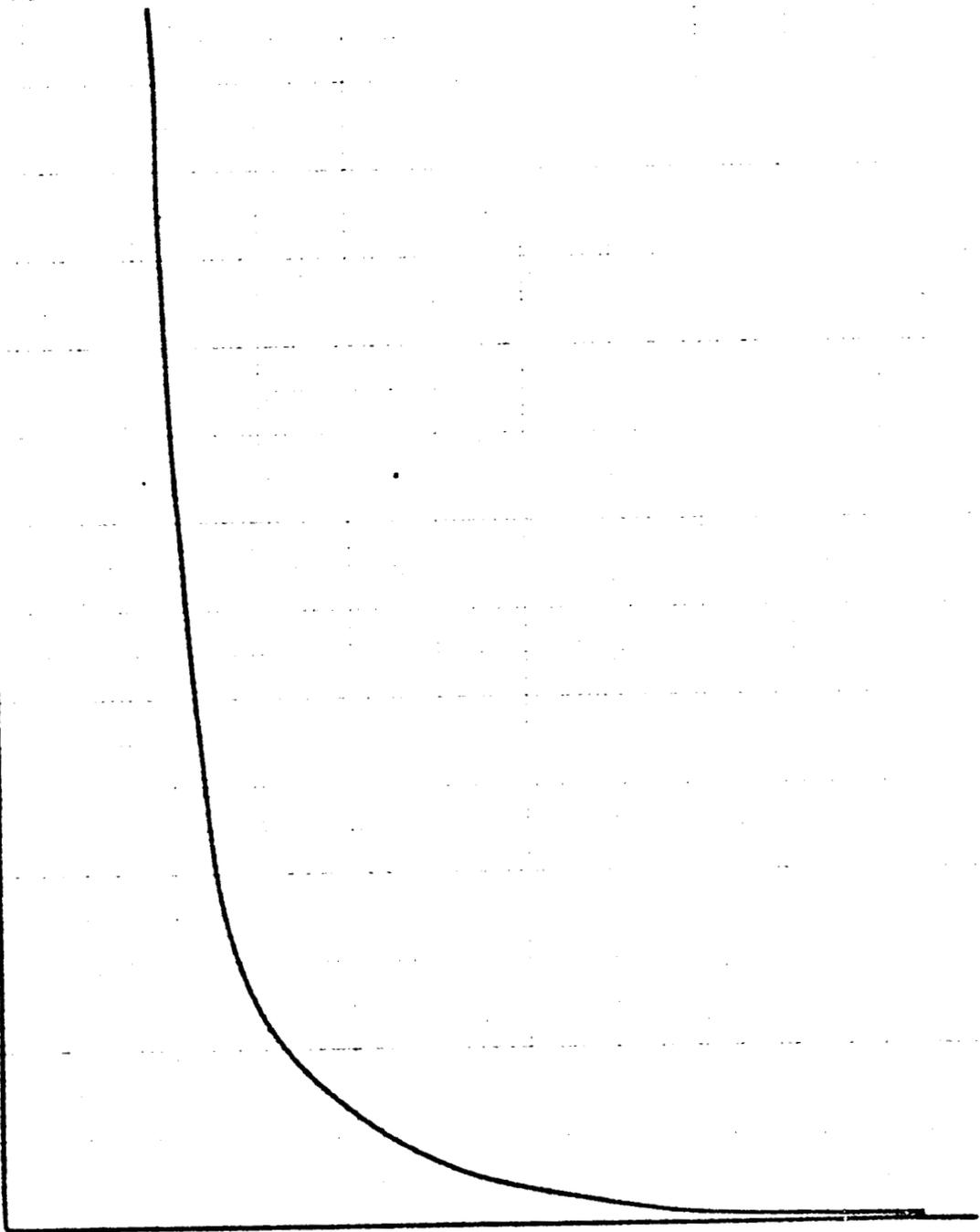
CONCLUSIONS

1. A plot of the rate at which CO_2 was pumped into CO_2 frost, when initially put in a CO_2 atmosphere, as a function of density is given in Figure 24. The graph has the general form of half of a parabola, the minimum occurring at a density of 15. lbs/ft³ and a cryopumping rate of zero SEFH.

THE RATE AT WHICH CO₂ IS SYNTHESIZED THROUGH

CO₂ PUMP AS A FUNCTION OF INITIAL pH

Rate of
CO₂
pumping



INITIAL pH

2. The density of CO_2 frozen in a helium atmosphere is a function of the CO_2 flow rate, chill down rate, temperature gradient, the partial pressure of helium and the length of time of freezing.
3. If CO_2 is frozen in quartz batting, in a 15. psia partial pressure of helium for six hours, the density of the resulting CO_2 frost, in pounds per cubic foot, is approximately equal to ten times the flow rate of the CO_2 in SCFM per square foot of cryogenic tank.
4. It is the writer's opinion that the slower chill rates yield the lower thermal conductivities. Experiments "H", "I" and "J" do not uphold this opinion, but they had very irregular shapes in the vicinity of the test chamber while experiments "B", "E" and "F" were very smooth and regular. This opinion is further based on a number of frost growths which had rapid chill rates. In all cases, with a rapid chill rate, the conductivity in the vicinity of the cryogenic wall was relatively high and the overall frost conductivity was correspondingly high.

REFERENCES

1. Ronney, E. Arthur: Engineering Supersonic Aerodynamics, McGraw-Hill Book Co., Inc., 1956.